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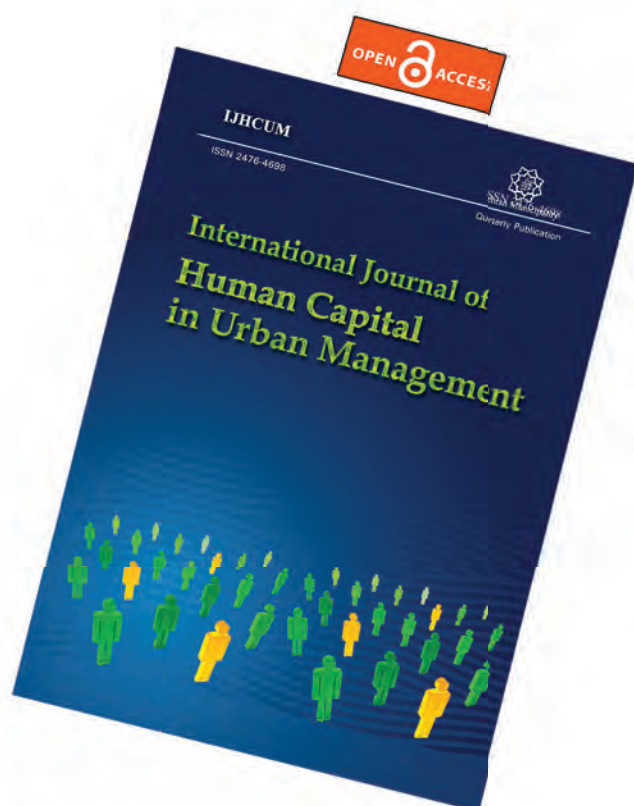
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ORIGINAL RESEARCH PAPER

Integrating smart technologies and sustainable infrastructure in the mango supply chain management for urban resilience

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ABSTRACT

BACKGROUND AND OBJECTIVES: Krishnagiri is a significant hub for mango cultivation, primarily producing varieties like 'Banginapalli,' 'Alphonso,' and 'Thothapuri.' Despite the region's favorable agro-climatic conditions, mango farming faces several challenges, including climate variability, inadequate infrastructure, and limited technology adoption. This study aims to analyze the dynamics of the mango supply chain in Krishnagiri, focusing on technology adoption, market access, infrastructure challenges, and government policies, with the primary objectives of identifying key barriers, assessing technology usage, and recommending interventions to enhance supply chain efficiency.

METHODS: A mixed-methods methodology was employed, combining quantitative, qualitative, and mixed-methods analyses. Quantitative data were collected through structured surveys with 150 mango farmers, 80 traders, and 30 government officials. The survey included Likert-scale and multiple-choice questions covering technology adoption, market access, and infrastructure. Qualitative data were gathered through in-depth interviews, focus group discussions, and field visits, providing deeper insights into stakeholder perceptions and challenges. Statistical tools like the Statistical Package for the Social Sciences and Excel were used for data analysis.

FINDINGS: The results show that 60% of farmers sell locally, 25% engage in export, and 15% rely on intermediaries. Technology use is low, with 68% reporting minimal digital tool adoption and only 12% using the Internet of Things or blockchain. Barriers to adoption affect 58%, with cost being the main issue for 40%. Infrastructure gaps are significant: 70% report inadequate cold storage, and 65% face transport issues like delays and poor roads, contributing to post-harvest losses. Water scarcity affects 62% due to groundwater overuse, and 45% report pest issues, mainly fruit flies and powdery mildew. Policy feedback is mixed, with 52% viewing government policies as effective while 48% cite poor local implementation. Encouragingly, 78% are willing to adopt new technologies if subsidized. Smart tech adoption remains low (mean 33.6%, benefit 27.4%, variance 32.64 and 31.04), and 55.6% are affected by logistics issues (severe impact variance 69.04). Farmer engagement shows high inconsistency (variance 356.9 vs. traders' 236.97), with positively skewed data emphasizing the need for targeted support.

CONCLUSION: The conclusion should highlight the importance of promoting digital tools and smart technologies, increasing Internet of Things and blockchain adoption (12%) through subsidies and digital literacy. By deploying smart logistics, it must address infrastructure gaps, with 70% lacking cold storage and 65% facing transport delays. Enhancing market access beyond local sales (60%) via Information and Communication Technology linkages is vital. Policy support through subsidies, awareness, and local implementation is needed. Future research should assess long-term tech adoption and policy impacts on urban resilience and smallholder sustainability.

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INTRODUCTION

Mango (*Mangifera indica* L.) is one of the most significant fruit crops globally, with India being the largest producer (Le *et al.*, 2022). Krishnagiri, a key mango-producing region in Tamil Nadu, is renowned for cultivating premium varieties such as 'Banginapalli,' 'Alphonso,' and 'Thothapuri' (Subanginidevi, 2025). Despite favorable agro-climatic conditions, mango cultivation in Krishnagiri faces multiple challenges, including climate variability (Tengsetasak *et al.*, 2024), infrastructure limitations (Wardhan *et al.*, 2022), market inefficiencies (Hagos *et al.*, 2020), and low technology adoption (Xie *et al.*, 2024). The growing demand for high-quality mangoes in domestic and international markets highlights the need for a well-integrated supply chain that incorporates modern agricultural technologies and sustainable farming practices (Kiloes *et al.*, 2024). Smart supply chain management strategies play a crucial role in optimizing mango production, post-harvest handling, and market access (Zahra *et al.*, 2024; Subanginidevi, 2025). Digital innovations such as blockchain, the Internet of Things (IoT), and geospatial analytics improve supply chain transparency, traceability, and decision-making (Enthoven and Van den Broeck, 2021). However, research indicates that smallholder farmers face barriers to adopting these technologies due to cost constraints, lack of awareness, and inadequate digital infrastructure (Kisumbi *et al.*, 2024). While prior studies have examined resource use efficiency (Barwal *et al.*, 2022), market participation (Taipour *et al.*, 2020), and mango production trends, there is a lack of comprehensive research on integrating digital innovations to optimize mango supply chains (Schubert *et al.*, 2017). Existing literature extensively covers consumer preferences for mangoes (Kiloes *et al.*, 2022), but limited attention has been given to how smart technologies can bridge the gap between producers and consumers through enhanced quality control and reduced post-harvest losses (Qanti *et al.*, 2017). Infrastructure and logistical challenges in mango supply chains have been explored (Lauricella *et al.*, 2017; Wardhan *et al.*, 2022; Laili *et al.*, 2024), but an integrated analysis of digital platforms for improving market access remains underdeveloped (Sandhu and El-Gohary, 2023). Studies such as Audate *et al.*, (2018) and Sathiyamurthi *et al.*, (2024) highlight the potential of geospatial and

machine learning methodologies in agriculture, but their specific applications in mango farming require further exploration. While research on high-density mango plantations (Sharma *et al.*, 2017; Kumar *et al.*, 2017) and pest management strategies (Manikandan *et al.*, 2021) focuses on productivity, insights into how technology-driven solutions can enhance yield prediction, quality assessment, and logistics remain limited (Pandey *et al.*, 2017). This study introduces a novel and comprehensive approach integrating advanced smart supply chain management strategies alongside traditional mango farming practices within Krishnagiri (Subanginidevi, 2025). Unlike previous research focusing primarily on production constraints (Ramu *et al.*, 2023) or market linkages (Sacramento and Geges, 2020), this study expands its scope through the exploration of emerging digital technologies. It examines how tools such as the IoT, blockchain technology, Artificial Intelligence (AI)-driven analytics, geospatial analysis, and digital traceability mechanisms enhance coordination across the entire mango supply chain. Improved real-time data sharing, transparency, and traceability reduce inefficiencies and minimize post-harvest losses, major challenges within traditional supply chains. Smart technologies empower farmers and stakeholders, optimizing resource use, enhancing decision-making, and increasing profitability, promoting economic viability alongside sustainability within the mango supply ecosystem. This integrative approach marks a significant advancement in applying technology-driven solutions tailored toward unique challenges faced by mango producers and supply chain actors amid rapid urbanization. The primary objective of this study is to analyze the current state of the mango supply chain in Krishnagiri, with a focus on technological adoption, infrastructure challenges, and market access. Specifically, it aims to (i) identify key barriers affecting supply chain efficiency, including climate variability, infrastructure limitations, and market constraints; (ii) assess the level of technology adoption among mango farmers, traders, and exporters, and evaluate the impact of digital tools on supply chain performance; (iii) evaluate infrastructure gaps, particularly in cold storage, transportation, and packaging, which contribute to post-harvest losses; (iv) analyze market access challenges and the role of intermediaries in influencing pricing and profitability for mango farmers; (v) examine the influence of digital

technologies, infrastructure quality, government policies, intermediary roles, stakeholder awareness, and smart city Information and Communication Technology (ICT) solutions on the efficiency, profitability, and performance of Krishnagiri's mango supply chain through integrated hypothesis testing (from H1 to H6); and (vi) recommend strategic interventions to enhance the adoption of smart supply chain management solutions, improve infrastructure, and strengthen market linkages. The findings from this study will support policymakers, agribusinesses, and farmers in modernizing mango production and improving global competitiveness. This study was conducted in December 2024 by researchers from Sri Vidya Mandir Arts and Science College, Uthangarai, and Kalasalingam Academy of Research and Education, Krishnakoil, Tamil Nadu, India.

MATERIALS AND METHODS

Mango cultivation practices and challenges in Krishnagiri

Study area

Krishnagiri district is located in the northwestern

part of Tamil Nadu, India (Fig. 1). It is bordered by the states of Andhra Pradesh and Karnataka to the north, and by the districts of Vellore and Tirupattur to the east, Dharmapuri to the south, and Salem to the west.

The district has a total area of 5,101 square kilometers (km²), and the district headquarters is located in the town of Krishnagiri. The district is known for its mangoes, which are cultivated in the Krishnagiri taluk. Other important crops include groundnut, sugarcane, and ragi. The district is also home to several industries, including textile, sugar, and cement. Krishnagiri district is located in the southern part of India, specifically in the state of Tamil Nadu. The latitude and longitude coordinates for Krishnagiri district are approximately 12° 31' 7"N latitude and 78° 12' 5"E longitude (Fig. 1). These coordinates pinpoint the central location of Krishnagiri district on the Earth's surface.

Mango cultivation practices in Krishnagiri

Krishnagiri district, located in Tamil Nadu, India, is renowned for its extensive mango cultivation, earning it the title "Mango Capital of India." The

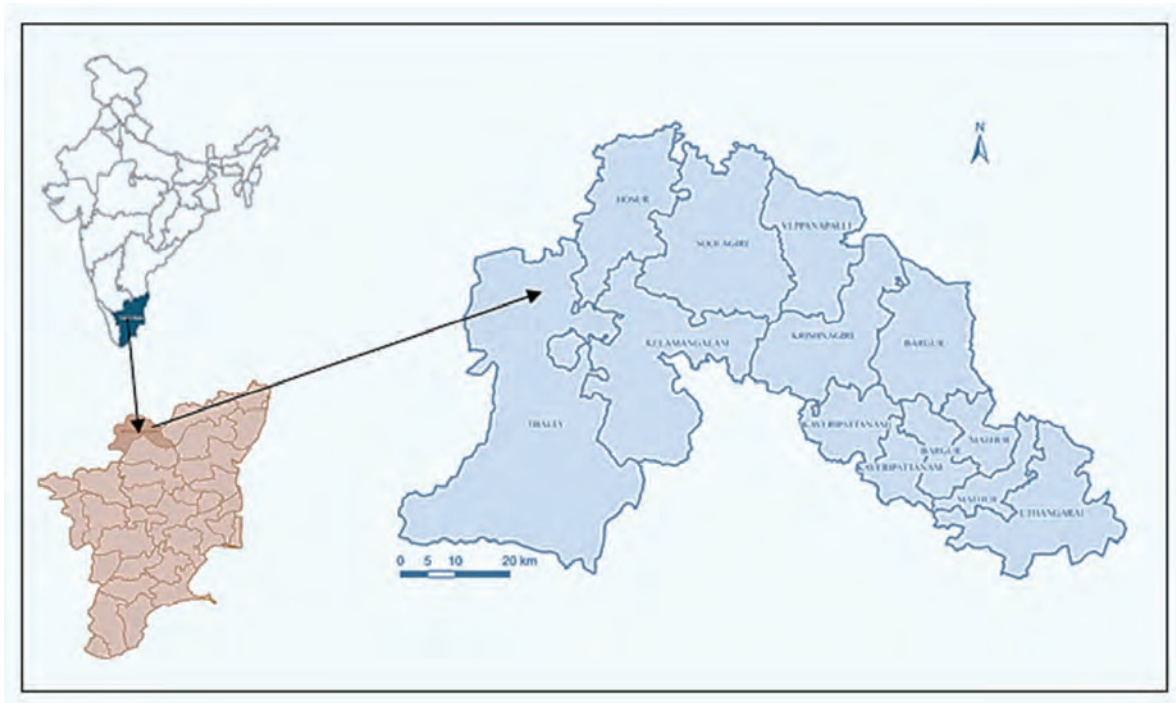


Fig. 1: Location map of Krishnagiri district (study area)

district's favorable agro-climatic conditions, including a moderate climate and fertile soil, make it ideal for mango farming. Predominantly, varieties such as 'Banginapalli' and 'Alphonso' are cultivated, with 'Thothapuri' also being significant. A study conducted in 2023 utilized Linear Imaging Self-Scanning Sensor IV (LISS IV) to map mango plantations in major blocks of Krishnagiri district (Roy *et al.*, 2018). The findings revealed that the total area under mango cultivation in these blocks was approximately 9,077.9 hectares, with an accuracy assessment of 91.2 percent (%), highlighting the reliability of satellite imagery in agricultural mapping. Further analysis of the socio-economic aspects of mango farming indicated that the average farm size is approximately 5.87 acres, with annual incomes averaging around USD 15,000. The study also highlighted that 60% of farmers sell their produce in local markets, 25% engage in export markets, and 15% rely on intermediaries (Elangovan *et al.*, 2017).

Key challenges in production

Mango cultivation in Krishnagiri faces multiple challenges that impact yield and sustainability. Climate variability, marked by unseasonal rains and temperature fluctuations, disrupts flowering and fruit setting, leading to inconsistent production. Land fragmentation complicates large-scale cultivation and the adoption of modern farming techniques. Irrigation constraints, due to over-reliance on groundwater and inefficient water management, contribute to water scarcity during crucial growth phases (Santhakumar *et al.*, 2019). Additionally, pest and disease management remains a significant concern, with fruit flies and powdery mildew posing threats to crop health. Effective control requires continuous monitoring and the adoption of integrated pest management strategies.

Data collection methodology

The study employed a mixed-methods methodology, integrating both quantitative and qualitative data collection techniques to ensure a comprehensive understanding of the agricultural supply chain in Krishnagiri. The methodology included the following key aspects:

i. Stratified sampling: Stratified sampling was employed to ensure representative sampling across Krishnagiri's diverse mango-growing regions. Five

taluks (Krishnagiri, Hosur, Pochampalli, Uthangarai, and Denkanikottai) were selected based on criteria such as mango cultivation intensity, agro-climatic variation, and supply chain activity levels. This stratification allowed for the inclusion of heterogeneous farming systems and infrastructure conditions, ensuring a comprehensive analysis of regional disparities in agricultural practices, technology adoption, and supply chain dynamics across the district (Thippeswamy and Yogish, 2023).

ii. Structured surveys and questionnaires: To collect quantitative data on key aspects of the agricultural supply chain, structured surveys were designed with a focus on infrastructure development, technology adoption, market trends, stakeholder engagement, and challenges (Bogachov *et al.*, 2022). These surveys targeted multiple stakeholders and included a combination of closed-ended and Likert-scale questions to facilitate numerical analysis and comparative evaluations (Wardhan *et al.*, 2022).

iii. Target audience and sample size: The study encompassed a diverse group of stakeholders, including mango farmers, traders, and government officials, to provide a comprehensive perspective on the supply chain. The sample distribution included 150 mango farmers, 80 traders and distributors, and 30 government officials and urban planners. Additionally, consumer surveys were conducted among urban buyers to understand demand trends and preferences. In total, 260 respondents participated in the study, ensuring a 95% confidence level with a 0.035% margin of error.

iv. Data collection methods: A mixed-methods methodology was adopted, integrating both primary and secondary data sources to enhance the reliability and depth of the findings. Primary data was gathered through structured surveys, interviews, focus group discussions, and field visits to mango farms and wholesale markets. Secondary data was sourced from government reports, census records, industry publications, and market research reports to validate primary findings and provide a broader contextual understanding (Xie *et al.*, 2024).

v. Language and cultural sensitivity: Recognizing the importance of effective communication, all survey instruments, interviews, and discussions were conducted in Tamil, the local language. This methodology ensured that respondents could comfortably express their views, leading to more

accurate and meaningful data collection while respecting cultural nuances.

vi. *Pilot testing*: To refine the research instruments, a pilot test was conducted with a small group of respondents. This pre-test helped identify ambiguities, improve clarity, and enhance the overall effectiveness of the questionnaires and data collection methods before full-scale implementation.

Data analysis

Quantitative methodology

The study employed structured surveys to collect numerical data from key stakeholders, including 150 mango farmers, 80 traders, and 30 government officials. The surveys captured insights on market access, infrastructure, technology adoption, and supply chain dynamics through closed-ended and Likert-scale questions. Data analysis was conducted using Statistical Package for the Social Sciences (SPSS) and Excel to identify patterns, calculate percentages, and determine adoption rates. Key topics included reliance on intermediaries, digital technology adoption (IoT, blockchain), infrastructure development, and consumer preferences, providing statistical insights into sectoral challenges and opportunities (Sathiyamurthi *et al.*, 2024).

Qualitative methodology

Qualitative data were gathered through in-depth interviews, focus group discussions, and field visits conducted across various locations in Krishnagiri. Semi-structured interviews with a purposively selected sample of farmers, traders, government officials, and technology providers were designed using an interview guide to ensure consistency while allowing flexibility to explore emerging insights. These interviews focused on stakeholder perceptions, technological barriers, infrastructure limitations, and adaptive strategies. Focus group discussions, organized within farming communities and trader associations, facilitated dynamic exchanges on issues such as market linkages, pricing structures, and policy interventions. Field visits to farms, collection centers, and wholesale markets provided observational data on logistical inefficiencies, including delays, post-harvest handling practices, and cold storage constraints. To identify key themes, data were coded inductively and deductively using thematic analysis, supported by qualitative software tools. Patterns

were triangulated across data sources to ensure validity, while interviewer bias was mitigated through interviewer training, use of standardized protocols, and member checking with participants to confirm interpretations (Schubert *et al.*, 2017).

Mixed-methods methodology

The study integrated quantitative and qualitative methodologies for a comprehensive analysis of Krishnagiri's agricultural supply chain. Structured surveys provided statistical insights, while qualitative methods enriched the findings with stakeholder perspectives and contextual challenges. This mixed-methods methodology enabled a holistic understanding of market access, infrastructure gaps, and technology adoption barriers, forming a robust framework for targeted interventions in the sector (Sharma *et al.*, 2017).

Hypotheses

These hypotheses are based on the quantitative and qualitative data gathered from the various stakeholders, including farmers, traders, government officials, and technology providers, to explore the dynamics of Krishnagiri's mango supply chain. The following hypotheses can be proposed for the study:

- i. H1: Adoption of digital technologies (IoT, blockchain, AI) positively influences the efficiency and profitability of the mango supply chain in Krishnagiri.
- ii. H2: The availability and quality of infrastructure (such as cold storage and transportation facilities) significantly impact market access and product quality in the mango supply chain.
- iii. H3: Government policies and interventions play a crucial role in enhancing the overall effectiveness of the agricultural supply chain, particularly in terms of infrastructure development and market linkages.
- iv. H4: The reliance on intermediaries in the mango supply chain negatively affects the profitability of farmers, with digital technologies and ICT-based market linkages offering potential solutions to reduce this dependency.
- v. H5: There is a significant correlation between the stakeholders' awareness and willingness to adopt new technologies and the rate of technology adoption in the agricultural supply chain.
- vi. H6: The role of smart cities and ICT-based solutions significantly contributes to addressing key challenges in the agricultural supply chain, including

Table 1: Demographic Profile of Respondents (Sample Size = 260)

Category	Mango Farmers (150)	Traders and Distributors (80)	Government Officials and Urban Planners (30)	Total Participants
Age				
Up to 20 Years	15 (10.0%)	5 (6.3%)	2 (6.7%)	22 (8.5%)
20-30 Years	40 (26.7%)	20 (25.0%)	5 (16.7%)	65 (25.0%)
30-40 Years	45 (30.0%)	25 (31.3%)	10 (33.3%)	80 (30.8%)
40-50 Years	30 (20.0%)	20 (25.0%)	8 (26.7%)	58 (22.3%)
50 Years and Above	20 (13.3%)	10 (12.5%)	5 (16.7%)	35 (13.5%)
Education Qualification				
Illiterate	12 (8.0%)	5 (6.3%)	0 (0.0%)	17 (6.5%)
Primary Education	18 (12.0%)	10 (12.5%)	2 (6.7%)	30 (11.5%)
High School Education	55 (36.7%)	30 (37.5%)	8 (26.7%)	93 (35.8%)
Graduates	30 (20.0%)	25 (31.3%)	15 (50.0%)	70 (26.9%)
Others	35 (23.3%)	10 (12.5%)	5 (16.7%)	50 (19.2%)
Annual Income				
Below ₹2 Lakhs	35 (23.3%)	10 (12.5%)	5 (16.7%)	50 (19.2%)
₹2 Lakhs – ₹4 Lakhs	60 (40.0%)	30 (37.5%)	10 (33.3%)	100 (38.5%)
₹4 Lakhs – ₹8 Lakhs	25 (16.7%)	25 (31.3%)	5 (16.7%)	55 (21.2%)
₹8 Lakhs – ₹10 Lakhs	15 (10.0%)	10 (12.5%)	5 (16.7%)	30 (11.5%)
Above ₹10 Lakhs	15 (10.0%)	5 (6.3%)	5 (16.7%)	25 (9.6%)

transportation inefficiencies, cold storage limitations, and market access.

Statistical analysis

The statistical analysis for this study employed both descriptive and general statistical methods to interpret data collected from surveys and questionnaires. Descriptive statistics, including mean, median, mode, range, variance, standard deviation, skewness, and kurtosis, were used to summarize key patterns, trends, and stakeholder perceptions within the agricultural supply chain. These measures helped capture central tendencies and variations across different variables, providing a clear picture of the data's distribution. General statistical analysis was applied to examine data distribution and uncover patterns related to stakeholder engagement, infrastructure adequacy, and technology adoption within the mango supply chain in Krishnagiri. SPSS and Excel were employed due to their user-friendly interfaces, robust analytical capabilities for handling survey data, and suitability for descriptive and inferential statistical procedures commonly used in agricultural supply chain research. These tools enabled the calculation of measures such as mean, median, variance, skewness, and kurtosis, which were critical for identifying central tendencies and variability in stakeholder responses. While advanced tools like 'R' and Python offer greater flexibility and

modeling capabilities, SPSS and Excel were selected to align with the practical needs of local researchers and policymakers who may be more familiar with these platforms. Additionally, the structured nature of the dataset did not require complex algorithmic modeling, making these tools appropriate for the scope of analysis. This statistical approach provided clear, actionable insights into systemic challenges and opportunities across the supply chain (Subanginidevi, 2025).

RESULTS AND DISCUSSIONS

Analytical framework

The analytical framework provides strategic recommendations to enhance mango cultivation and marketing by leveraging opportunities, mitigating risks, and improving supply chain efficiency. It offers insights into product innovation, branding, market expansion, legislative advocacy, and technological adoption. This structured methodology helps stakeholders identify key challenges and formulate actionable strategies for maximizing the sector's potential (Schubert et al., 2017). Table 1 consolidates the demographic profiles of mango farmers, traders and distributors, and government officials and urban planners under common categories for easier comparison across different respondent groups.

From Table 1, it may be noted that the demographic profile of the study participants reveals

a diverse yet balanced representation across age, education, and income categories within the mango supply chain. A majority of participants in all groups, mango farmers (150), traders and distributors (80), and government officials and urban planners (30), fall within the productive age range of 20-40 years, with mango farmers showing the highest concentration in the 30-40 years group (30.0%). In terms of education, a notable proportion of farmers (36.7%) have at least a high school education, while traders and distributors and government officials generally have higher education levels, with 31.3% of traders holding graduate degrees and 50.0% of government officials being graduates. Income-wise, most farmers (40.0%) earn between ₹2 Lakhs and ₹4 Lakhs, reflecting the modest earnings typical in the agricultural sector. At the same time, traders and distributors tend to earn slightly higher incomes, with 31.3% earning between ₹4 Lakhs and ₹8 Lakhs. Government officials also fall in the ₹2 Lakhs – ₹4 Lakhs range (33.3%), with income spread evenly across other brackets. This data underscores a youthful, moderately educated, and economically diverse workforce, pointing to both the challenges and opportunities for growth and innovation within the mango supply chain, particularly in improving market access and income levels for lower-earning participants (Ramu *et al.*, 2023).

Evaluating the mango supply chain

This study employs a combination of quantitative, qualitative, and mixed-methods methodologies to analyze the mango supply chain in Krishnagiri. The quantitative analysis provides clear data on adoption rates, market trends, and technology use, while qualitative methods offer deeper insights into stakeholder perceptions and challenges (Sacramento and Geges, 2020). The mixed-methods methodology integrates both perspectives, providing a comprehensive understanding of the factors affecting supply chain efficiency, market trends, and policy impact, thereby enabling more targeted interventions.

Quantitative methodology

The quantitative methodology of the agricultural supply chain in Krishnagiri highlights key challenges and opportunities, particularly in storage, transportation, and digital adoption. Stakeholders

are increasingly exploring smart logistics, IoT, and electronic commerce solutions to enhance efficiency and market access. Government policies and smart city initiatives play a crucial role in driving sustainable growth in the sector (Sandhu and El-Gohary, 2023).

Existing supply chain structure

The agricultural supply chain in Krishnagiri involves key distribution and sales channels for farmers and traders. As shown in Fig. 2, 72% of farmers and 65% of traders rely on middlemen, limiting the adoption of smart urban management strategies (Wardhan *et al.*, 2022; Ravindran *et al.*, 2024). Additionally, 55% of farmers and 60% of traders use wholesale markets, exposing them to price fluctuations. Direct farm-to-consumer sales remain low, with only 30% of farmers and 20% of traders participating, highlighting the need for better market integration. Retail partnerships involve 40% of farmers and 50% of traders, indicating potential for digital and e-commerce-driven distribution (Hosseini *et al.*, 2020). The export sector remains underdeveloped, with only 20% of farmers and 30% of traders engaged. Furthermore, 38% of farmers and 45% of traders use digital platforms, showing a growing but limited adoption of smart logistics solutions (Xie *et al.*, 2024). These findings emphasize the need to reduce middlemen reliance, expand direct sales, strengthen digital infrastructure, and enhance export opportunities.

Challenges in storage, transportation, and distribution

The challenges in mango storage, transportation, and distribution in Krishnagiri present significant barriers to supply chain efficiency. As shown in Fig. 3, 65% of stakeholders identify poor transportation and road conditions as major challenges, with 50% reporting severe impacts on timely delivery, highlighting the need for improved rural transport networks (Thippeswamy and Yogish, 2023). Additionally, 58% of stakeholders face high storage costs and inadequate cold storage, with 45% considering it a severe issue, limiting product quality and farmer profitability. Post-harvest losses due to spoilage affect 60% of stakeholders, with 48% reporting significant spoilage, underscoring gaps in storage infrastructure (Tengsetasak *et al.*, 2024). Furthermore, 50% lack access to digital tracking and logistics systems, emphasizing the need for IoT-enabled solutions to optimize distribution. Payment delays from urban retailers impact 45% of stakeholders, with

Smart tech and sustainable infrastructure in mango supply chains for urban resilience

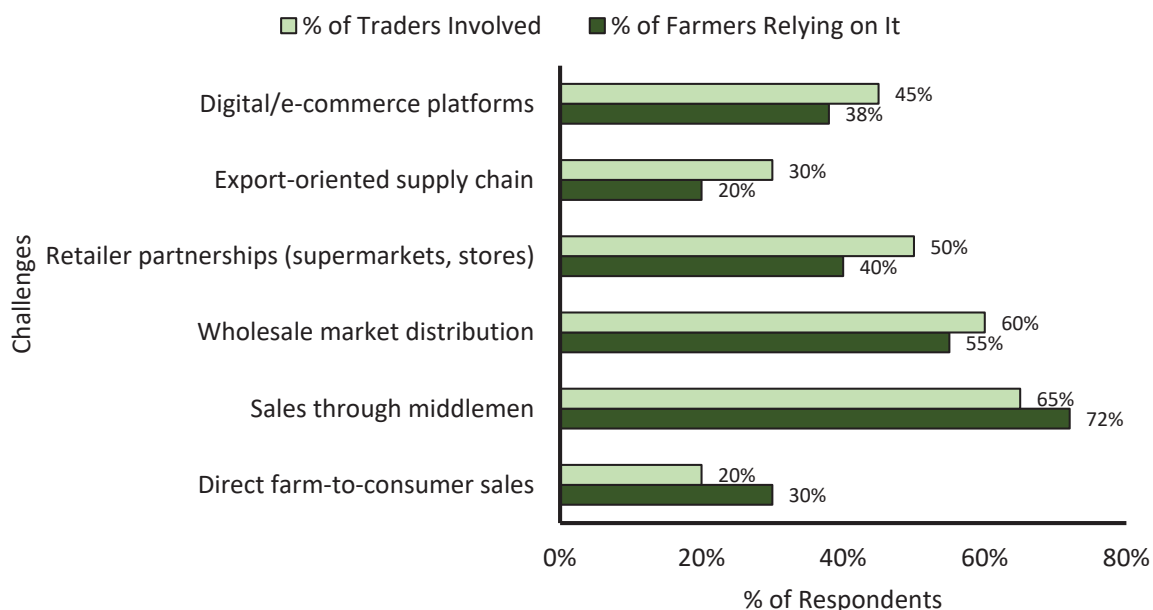


Fig. 2: Engagement of farmers and traders across various agricultural supply chain components

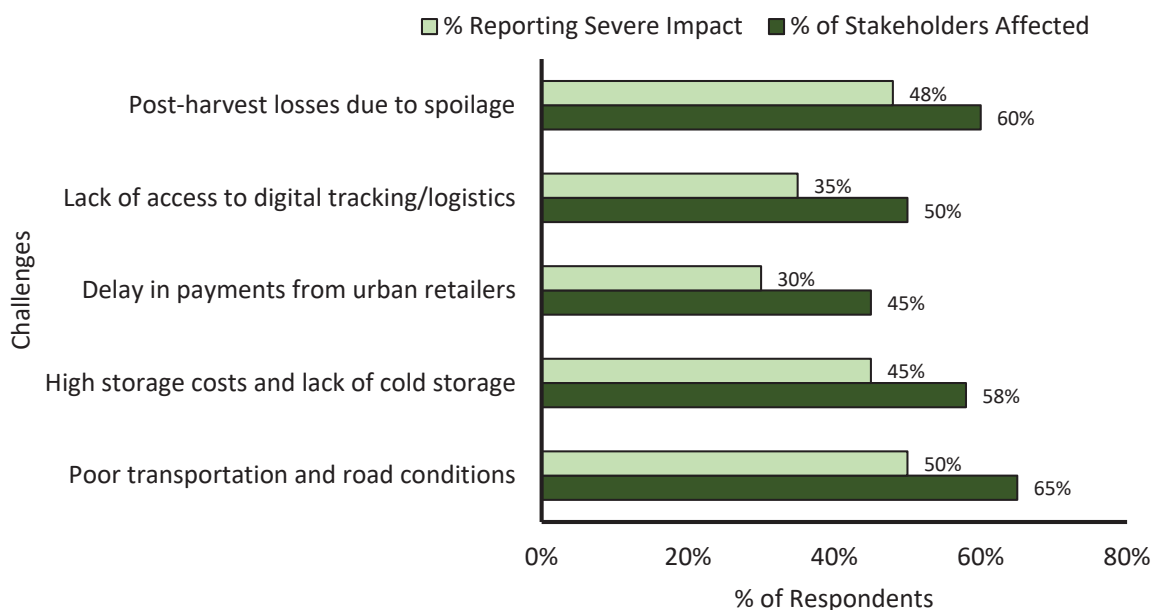


Fig. 3: Key storage, transportation, and distribution challenges in the mango supply chain

30% experiencing severe financial strain, calling for efficient digital payment systems. These findings stress the need for smart urban interventions, infrastructure investment, and digital integration to enhance mango supply chain operations.

Role of smart logistics and IoT in improving supply chain efficiency

The adoption of smart logistics and IoT technologies is crucial for improving the mango supply chain in Krishnagiri. As shown in Fig. 4, 40%

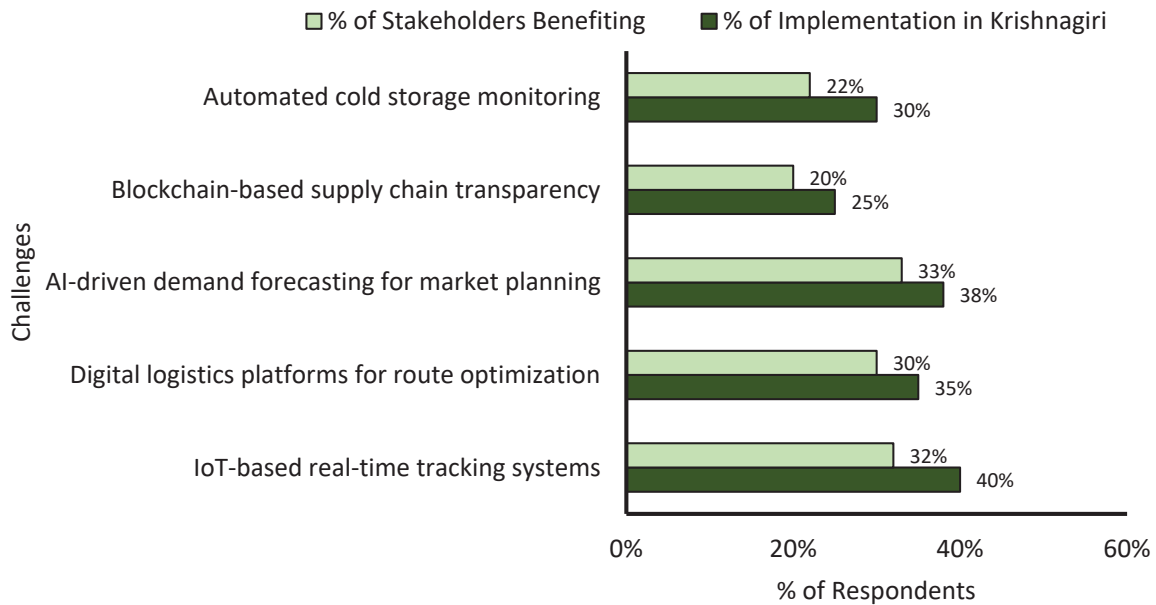


Fig. 4: Survey results on smart logistics and IoT adoption in Krishnagiri

of stakeholders use IoT-based real-time tracking, but only 32% benefit, indicating gaps in full-scale adoption. Additionally, 35% have implemented digital logistics for route optimization, with 30% benefiting, showing potential for cost reduction (Subanginidevi, 2025). AI-driven demand forecasting is used by 38% of stakeholders, with 33% benefiting, while blockchain-based transparency adoption remains low at 25%, with only 20% seeing results (Sushil et al., 2019). Furthermore, 30% have adopted automated cold storage monitoring, but just 22% benefit, underscoring the need for further investment. These findings emphasize the need for greater adoption of IoT, AI, and blockchain to enhance efficiency and transparency in mango distribution.

Market trends and consumer preferences

Understanding market trends and consumer preferences is key to shaping the future of mango distribution and cultivation in Krishnagiri. As shown in Fig. 5, 55% of traders report rising demand for organic mangoes, aligning with 50% of consumers who prefer them, indicating a shift toward healthier products (Sharma et al., 2017). Additionally, 48% of traders note a growing preference for pre-packaged mangoes, with 52% of consumers favoring this convenience,

highlighting the role of packaging in purchasing decisions. Interest in export-quality mangoes is observed by 40% of traders, with 35% of consumers preferring premium varieties. Furthermore, 45% of traders and 42% of consumers support direct farm-to-consumer sales, showing potential for expanding these channels (Schubert et al., 2017). Lastly, 50% of traders and 55% of consumers are willing to pay a premium for pesticide-free mangoes, emphasizing the focus on food safety. These findings highlight opportunities to meet consumer demand by prioritizing organic products, enhancing packaging, and expanding direct sales models.

Government policies and infrastructure development

Government policies and infrastructure drive economic growth by integrating advanced technologies and sustainable solutions. Fig. 6 illustrates that 40% of stakeholders have implemented smart logistics, but only 35% benefit, indicating the need for wider adoption (Ramu et al., 2023). Similarly, 35% use government-led e-commerce platforms, with 30% benefiting, highlighting digital literacy challenges. Public-private agro-tech partnerships involve 30% of stakeholders, yet only 25% benefit, stressing the need for better coordination.

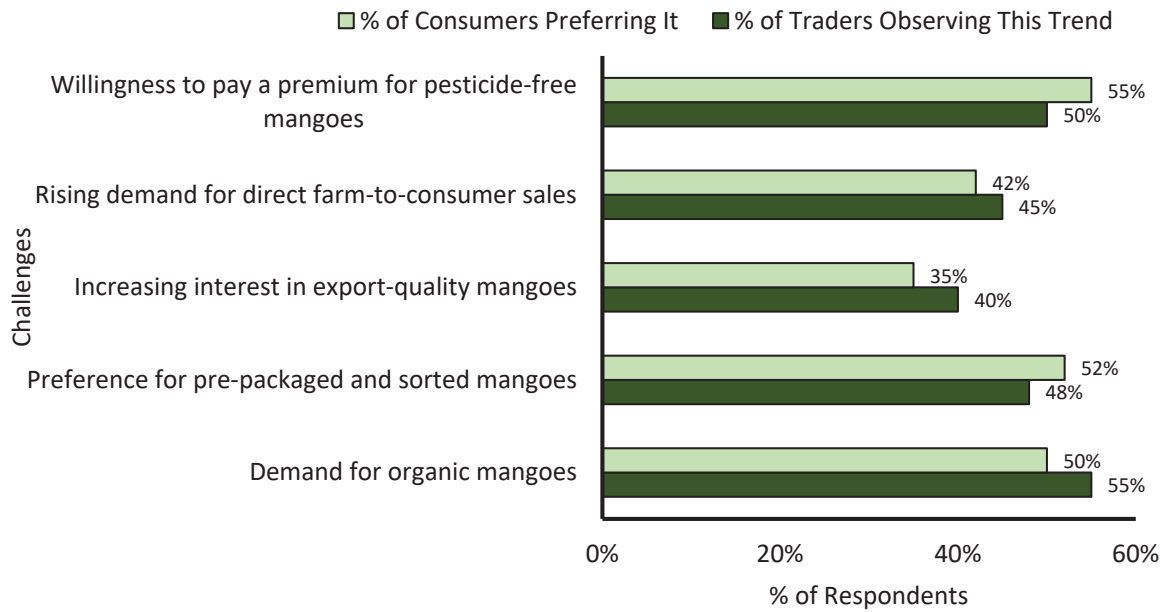


Fig. 5: Survey results on market trends and consumer preferences in mango distribution

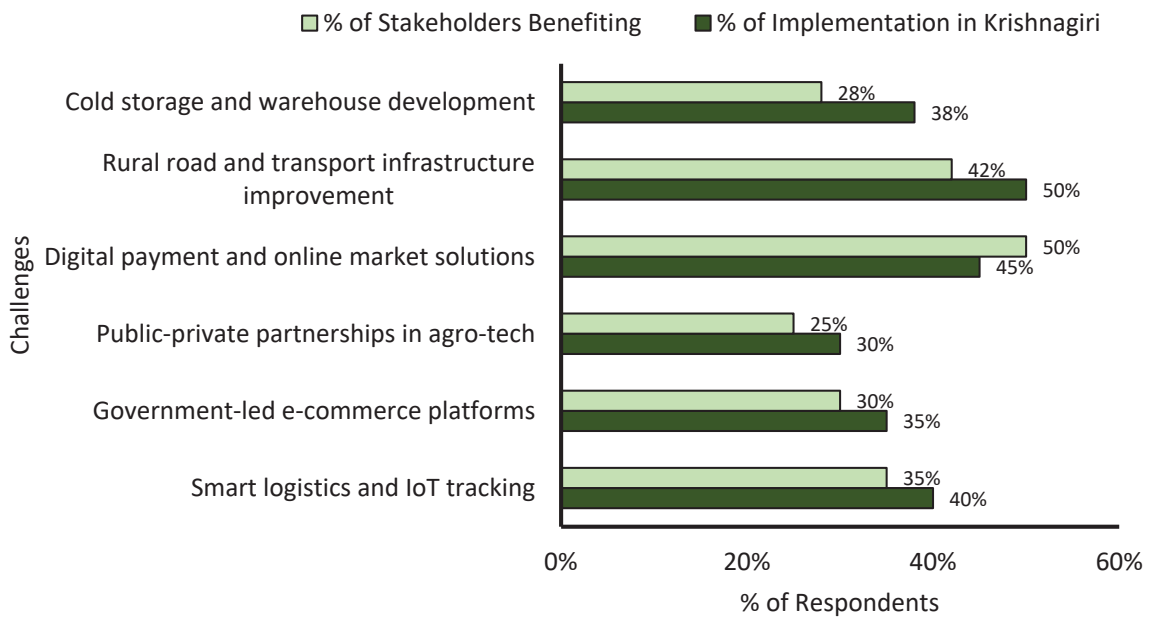


Fig. 6: Policy and Infrastructure Initiatives in the mango supply chain

Additionally, 45% have adopted digital payments, with 50% benefiting, though rural connectivity remains a barrier (Sacramento and Geges, 2020). While 50% have improved rural transport, only 42% see gains, and cold storage adoption by 38% benefits just 28%,

underscoring it as a major bottleneck. These findings emphasize the need for continued investment in logistics, digital platforms, and infrastructure to enhance the agro-supply chain and drive sustainable growth.

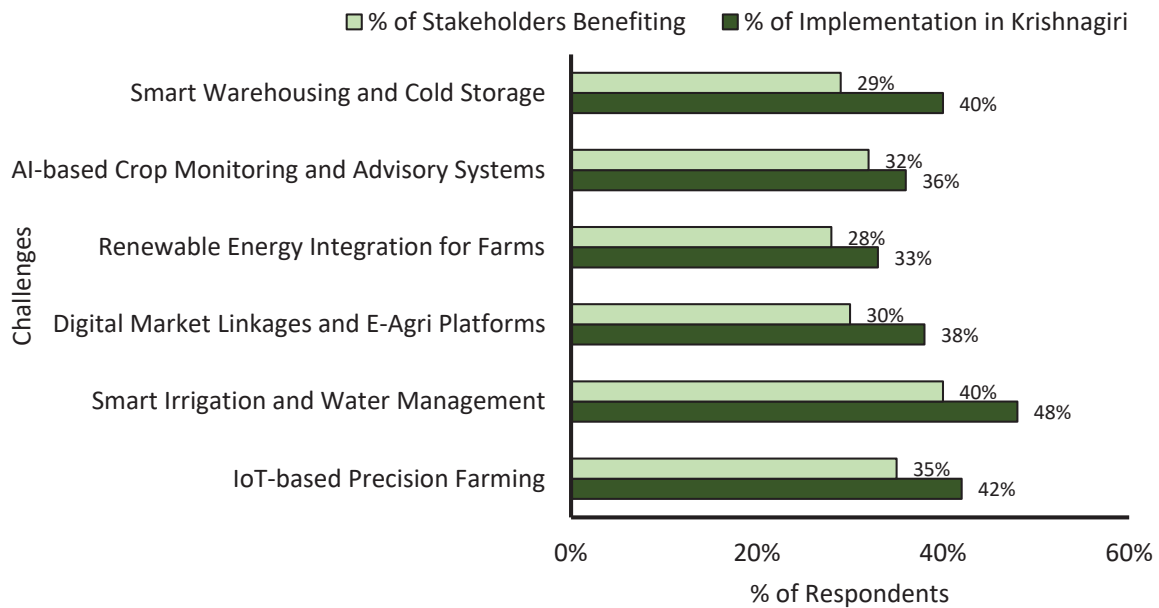


Fig. 7: Smart city initiatives and agricultural development in the mango supply chain

Role of smart cities in agricultural development

Smart city initiatives are playing a growing role in agricultural development by leveraging technology to improve productivity, sustainability, and market access. Fig. 7 shows that 42% of stakeholders have implemented IoT-based precision farming, but only 35% benefit, highlighting both potential and scaling challenges (Pandey *et al.*, 2017). Additionally, 48% have adopted smart irrigation, with 40% benefiting, reflecting improved water efficiency. Digital market linkages and e-agri platforms are used by 38% of stakeholders, yet only 30% benefit, indicating limited reach (Pandey *et al.*, 2017). Renewable energy integration remains slower, with 33% adoption and 28% benefiting. AI-based crop monitoring is used by 36% of stakeholders, benefiting 32%, while smart warehousing and cold storage adoption stands at 40%, with only 29% benefiting, underscoring the need for further investment (Qanti *et al.*, 2017). These findings suggest that while smart city initiatives are advancing agriculture, additional support is needed to maximize their impact and reach more stakeholders.

Adoption of ICT-based market linkages and e-commerce solutions

ICT-based market linkages and e-commerce solutions are improving market access and supply

chain efficiency in the mango sector. Fig. 8 shows that 38% of farmers use mobile apps like electronic National Agriculture Market (eNAM) and AgriBazaar for direct selling, reducing reliance on intermediaries (Sandhu and El-Gohary, 2023). Digital payments have been adopted by 50%, marking a shift toward cashless transactions for greater transparency. Blockchain-based tracking is used by 25%, reflecting efforts to enhance supply chain traceability. Additionally, 30% of farmers engage in online Business-to-Business (B2B) market access, creating export opportunities, though further expansion is needed (Sathiyamurthi *et al.*, 2024). While 35% of stakeholders report benefits from these ICT solutions, adoption remains limited. These findings highlight the need for further investment in infrastructure, training, and market expansion to maximize the impact of digital tools in the mango supply chain.

The mango supply chain in Krishnagiri faces challenges in storage, transportation, and market access, but smart logistics, IoT, and digital platforms are gradually improving efficiency. Government policies, infrastructure development, and smart city initiatives are driving progress, though greater investment in cold storage, digital literacy, and supply chain transparency is needed. Expanding ICT adoption, enhancing direct farm-to-consumer sales,

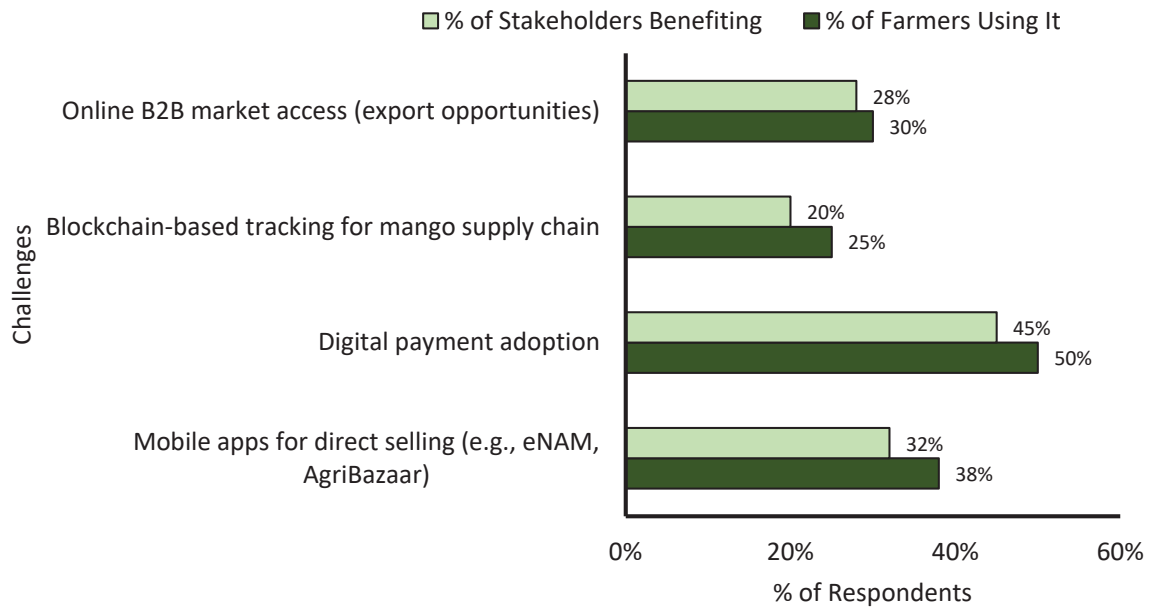


Fig. 8: Adoption of ICT-based market linkages and e-commerce solutions in the mango supply chain

and strengthening export opportunities can further optimize the agro-supply chain and increase farmer profitability.

The agricultural supply chain at Krishnagiri shows structural and technological gaps hindering efficiency and inclusivity, illustrated through Figs. 2–8. Fig. 2 reveals high dependence on middlemen (72% farmers, 65% traders) and low participation in direct-to-consumer sales, exposing the system to price fluctuations and undermining digital integration. Fig. 3 highlights acute infrastructure challenges with 65% facing poor transport, 58% inadequate cold storage, and 60% post-harvest spoilage, emphasizing the need for smart logistics and improved storage. Despite growing interest in smart solutions (Fig. 4), IoT, AI, and blockchain adoption remain limited, with only 32–35% stakeholders reporting tangible benefits. Market preference data in Fig. 5 indicates consumer shifts toward organic, packaged, premium mangoes, revealing alignment gaps between supply and demand. Government interventions (Fig. 6) show partial success regarding logistics and digital platforms, but issues like limited rural connectivity and coordination persist. Smart city initiatives (Fig. 7) offer promise, such as IoT-based farming and smart irrigation, yet show inconsistent uptake and benefits. Fig. 8 confirms rising use of ICT and e-commerce tools,

including eNAM, but adoption and effectiveness are constrained by access and digital literacy. Collectively, these visualizations underscore the urgent need for policy-driven investments, stakeholder training, and infrastructure upgrades aimed at transitioning toward a resilient, digitally integrated mango supply chain.

Qualitative methodology

The qualitative methodology provides insights into the mango supply chain, highlighting the dependence on middlemen, limited market access, and the need for better infrastructure and digital solutions. Key challenges include poor transportation, lack of cold storage, delayed payments, and limited digital tracking. Market trends, such as the demand for organic and pesticide-free mangoes, emphasize the need for investment in infrastructure, technology, and training. Government policies, smart city initiatives, and ICT adoption can improve supply chain efficiency, reduce losses, and enhance market access, fostering sustainable growth in the mango industry.

Existing supply chain structure

Table 2 illustrates the varying degrees of involvement of farmers and traders in different stages of the mango supply chain, highlighting the reliance on middlemen, direct sales, wholesale markets,

Table 2: Engagement of farmers and traders across agricultural supply chain components

Supply chain component	Qualitative insights
Direct farm-to-consumer sales	Limited market access and consumer awareness issues; farmers have few direct channels. Need for market linkages and consumer outreach.
Sales through middlemen	Heavy reliance on intermediaries is reducing profitability for both farmers and traders. A need to reduce middlemen and create direct sales channels.
Wholesale market distribution	Exposure to price fluctuations. Improved direct linkages with retailers or direct market access could stabilize prices and reduce risks.
Retailer partnerships	Growing potential for direct collaboration with retailers. More partnerships could lead to higher market penetration and more stable demand.
Export-oriented supply chain	Underdeveloped export market; this indicates a need for greater focus on export infrastructure, quality certification, and international trade opportunities.
Digital/e-commerce platforms	Growing but limited adoption of digital tools. Increased investment in technology infrastructure and digital literacy programs is needed.

Table 3: Storage, transportation, and distribution challenges

Challenge	Qualitative insights
Poor transportation and road conditions	Infrastructure bottlenecks cause significant distribution delays. Investment in rural transport networks is needed for efficient market access.
High storage costs and a lack of cold storage	High post-harvest losses and storage inefficiencies due to the lack of cold storage. A critical gap exists in cold storage infrastructure, requiring government-backed investments.
Delay in payments from urban retailers	Cash flow issues for farmers and traders. Streamlined payment systems and digital transaction platforms could resolve these delays.
Lack of access to digital tracking/logistics	Lack of transparency and real-time data in logistics. Adoption of IoT-based tracking systems can optimize routes and provide visibility in supply chains.
Post-harvest losses due to spoilage	Spoilage due to poor handling and storage conditions. Cold storage development and improved handling practices could reduce losses.

retail partnerships, and export opportunities, with varying adoption rates of digital and e-commerce platforms that reflect the market dynamics and the accessibility of alternative distribution channels for both stakeholders. From [Table 2](#), it is clear that farmers and traders face limited access to direct sales channels, relying heavily on middlemen, which reduces profitability. Wholesale markets expose them to price volatility, while digital platforms offer growth potential but require more infrastructure and literacy programs ([Audate et al., 2018](#)). Export-oriented chains are underdeveloped, signalling a need for better export infrastructure. These findings suggest that direct sales and digital tools need to be optimized to improve supply chain efficiency and market access ([Barwal et al., 2022](#)).

Challenges in storage, transportation, and distribution

[Table 3](#) identifies key challenges in the mango supply chain, including poor infrastructure, lack of cold storage, delayed payments, and limited access to digital tracking. Addressing these issues through

targeted investments and digital solutions could improve efficiency, reduce losses, and streamline operations for all stakeholders. From [Table 3](#), it may be observed that transportation issues, lack of cold storage, and post-harvest losses remain major challenges, requiring investment in infrastructure and cold storage systems. Payment delays from urban retailers and limited access to digital logistics hinder supply chain efficiency, highlighting the need for streamlined payment systems and IoT tracking adoption ([Camacho et al., 2021](#)). The integration of smart logistics solutions and infrastructure improvements could substantially mitigate post-harvest losses and enhance supply chain performance ([Enthoven and Van den Broeck, 2021](#)).

Role of smart logistics and IoT in improving supply chain efficiency

[Table 4](#) highlights the adoption of smart logistics and IoT technologies in the mango supply chain. From [Table 4](#), it may be observed that IoT-based real-time tracking systems have moderate adoption,

Table 4: Smart logistics and IoT adoption

Smart logistics and IoT initiative	Qualitative insights
IoT-based real-time tracking systems	Moderate adoption; greater affordability and training needed. Implementing IoT technologies can enhance visibility and efficiency in the supply chain.
Digital logistics platforms	Initial implementation: These platforms can significantly improve route optimization and supply chain management, but widespread adoption remains a challenge.
AI-driven demand forecasting	Potential to improve forecasting and inventory management, but low adoption indicates the need for education and AI solution integration.
Blockchain-based supply chain transparency	Limited adoption, though highly beneficial for traceability and security in the supply chain. Promoting blockchain technologies can enhance consumer trust and product quality verification.
Automated cold storage monitoring	Promising technology, but still facing barriers like cost and scalability. Investment in automated monitoring systems could reduce spoilage and improve cold storage efficiency.

Table 5: Market trends and consumer preferences

Market trend / Consumer preference	Qualitative insights
Demand for organic mangoes	Strong growth in the organic market. Certification and organic farming practices should be expanded to meet this rising consumer demand.
Preference for pre-packaged and sorted mangoes	Rising demand for convenience and consistent quality. Strengthening packaging and sorting infrastructure will meet this trend.
Increasing interest in export-quality mangoes	Export opportunities need improved certifications, quality control, and marketing strategies to meet the growing demand for high-quality mangoes.
Rising demand for direct farm-to-consumer sales	Growing trend for direct sales. Enhancing farm-to-consumer platforms like e-commerce and farmer cooperatives will align with consumer demand.
Willingness to pay a premium for pesticide-free mangoes	Increasing willingness to pay for pesticide-free mangoes. This trend calls for expanding sustainable farming practices and pesticide-free certifications.

with challenges in affordability and training, but they can improve visibility and efficiency. Digital logistics platforms are in early stages, offering potential for better route optimization, though broader adoption is needed (Hagos *et al.*, 2020). AI-driven demand forecasting shows promise for improving inventory management, but low adoption suggests the need for further education. Blockchain technology, while beneficial for traceability, is underutilized, and investment in automated cold storage monitoring could reduce spoilage and enhance efficiency despite cost and scalability challenges (Kiloes *et al.*, 2022).

Market trends and consumer preferences

Table 5 highlights key market trends and consumer preferences in the mango supply chain. From Table 5, it may be observed that there is strong growth in demand for organic mangoes, requiring expanded certification and farming practices. The preference for pre-packaged and sorted mangoes reflects the need for improved packaging and sorting infrastructure. Increasing interest in export-

quality mangoes calls for better certifications and marketing strategies (Kiloes *et al.*, 2024). The trend toward direct farm-to-consumer sales highlights the importance of enhancing e-commerce and farmer cooperatives. Lastly, the willingness to pay a premium for pesticide-free mangoes emphasizes the need for expanded sustainable practices and certifications (Le *et al.*, 2022).

Government policies and infrastructure development

Table 6 highlights key government policies and infrastructure developments in the mango supply chain. From Table 6, it may be observed that smart logistics and IoT tracking require more affordable access and training for farmers and traders. Government-led e-commerce platforms are crucial for integrating farmers into the digital economy, supported by digital literacy initiatives. Progress in public-private agro-tech partnerships has been slow, needing more investment and collaboration (Kiloes *et al.*, 2022). While digital payment systems are improving financial inclusion, rural connectivity

Table 6: Government policies and infrastructure development

Policy / Infrastructure initiative	Qualitative insights
Smart logistics and IoT tracking	Moderate uptake; more targeted efforts in affordability and training could ensure better access to IoT technologies for farmers and traders.
Government-led e-commerce platforms	E-commerce growth is necessary to integrate farmers into the digital economy. Digital literacy initiatives and access to technology are critical.
Public-private partnerships in agro-tech	Slow progress in agro-tech partnerships; more collaboration and investment needed to scale up IoT, AI, and blockchain solutions in agriculture.
Digital payment and online market solutions	High adoption of digital payment systems is improving financial inclusion, but rural connectivity remains a challenge that needs addressing.
Rural road and transport infrastructure improvement	Transport improvements have made strides, but further expansion is needed to improve last-mile delivery and reduce logistical costs.
Cold storage and warehouse development	Underdeveloped cold storage continues to be a bottleneck. Expanding cold storage infrastructure is essential for reducing post-harvest losses and improving food security.

Table 7: Role of smart cities in agricultural development

Smart city initiative	Qualitative insights
IoT-based precision farming	Moderate adoption of IoT in farming. Expanding precision farming technologies can optimize resource use and increase crop yields while improving sustainability.
Smart irrigation and water management	Increasing implementation of smart irrigation systems. Expanding water management technologies could improve water efficiency and lower costs for farmers.
Digital market linkages and e-agri platforms	E-agri platforms offer opportunities for better market access but need more training and infrastructure to improve accessibility, especially in rural areas.
Renewable energy integration for farms	Renewable energy integration is nascent, but it can offer cost savings and environmental benefits. Government incentives can further promote this trend.
AI-based crop monitoring and advisory systems	AI technologies can enhance crop monitoring and provide timely advisories, improving farm productivity and reducing risks.
Smart warehousing and cold storage	Smart cold storage technologies can reduce post-harvest losses and ensure better quality control, requiring greater investments in this area.

remains a challenge. Transport improvements are progressing but need further expansion, and cold storage infrastructure remains underdeveloped, requiring expansion to reduce post-harvest losses (Pandey *et al.*, 2017).

Role of smart cities in agricultural development

Table 7 highlights the role of smart cities in agricultural development. From Table 7, it may be observed that IoT-based precision farming has moderate adoption, with potential to optimize resource use and increase crop yields. Smart irrigation systems are improving water efficiency, while digital market linkages and e-agri platforms require more infrastructure and training, particularly in rural areas. Renewable energy integration is in early stages but offers cost savings and environmental benefits (Le *et al.*, 2022). AI-based crop monitoring can enhance productivity, and smart cold storage technologies can reduce post-harvest losses, though investment is needed in both areas (Pandey *et al.*, 2017).

Adoption of ICT-based market linkages and e-commerce solutions

Table 8 highlights the adoption of ICT-based market linkages and e-commerce solutions in the mango supply chain. From Table 8, it may be observed that the use of mobile apps for direct selling, such as eNAM and AgriBazaar, is limited but growing, with increased awareness and training needed to expand usage. Digital payment adoption is high, though rural connectivity challenges remain, requiring continued investment in digital literacy and payment infrastructure (Sacramento and Geges, 2020). Blockchain-based tracking is minimally adopted but offers significant opportunities for improving transparency and traceability in the supply chain. Online B2B market access has seen moderate adoption, with further integration needed to fully capitalize on export opportunities and increase market access and revenue (Sharma *et al.*, 2017).

The adoption of ICT-based market linkages and e-commerce solutions in the mango supply

Table 8: Adoption of ICT-Based Market Linkages and E-Commerce Solutions

E-commerce and ICT adoption	Qualitative insights
Mobile apps for direct selling (e.g., eNAM, AgriBazaar)	Limited but growing use of digital platforms for direct sales. Increasing awareness and training programs can expand usage.
Digital payment adoption	High adoption, but challenges related to rural connectivity persist. Continued investment in digital literacy and payment infrastructure is necessary.
Blockchain-based tracking for the mango supply chain	Low adoption of blockchain, though it offers opportunities for transparency and traceability. Promotion of blockchain can help improve supply chain efficiency.
Online B2B market access (export opportunities)	Moderate adoption of online B2B platforms; further integration with export opportunities is necessary to maximize market access and revenue.

chain is growing but remains limited. Mobile apps for direct selling and digital payments are gaining traction, though rural connectivity challenges persist. Blockchain tracking and online B2B market access offer significant opportunities, requiring further investment in awareness, infrastructure, and integration to maximize market potential.

Mixed-methods methodology

The mixed-methods methodology used in this study combines both quantitative data and qualitative insights to provide a comprehensive analysis of the mango supply chain in Krishnagiri. The quantitative data, including adoption rates, market trends, and infrastructure challenges, offers measurable insights into the current state of the supply chain (Schubert et al., 2017). Meanwhile, qualitative insights complement this by exploring the underlying reasons behind these trends, such as the heavy reliance on middlemen, infrastructure gaps, and the potential of smart technologies like IoT and digital platforms. Together, these methods offer a well-rounded understanding of the key issues and opportunities, guiding potential interventions and improvements for the mango industry (Sacramento and Geges, 2020). Table 9 highlights key challenges, technological adoption, market trends, and government policies impacting the mango industry in Krishnagiri, providing a comprehensive overview of opportunities for improvement and growth.

The mango supply chain in Krishnagiri faces several challenges and opportunities that impact its efficiency and growth. Key insights from the study reveal critical areas that need improvement and investment for enhancing the sector's performance and sustainability.

1. *Supply chain structure:* A high reliance on middlemen and wholesale markets limits efficiency

and market access. A shift towards direct farm-to-consumer sales and digital platforms is essential for improving distribution.

2. *Infrastructure challenges:* Poor roads, high storage costs, and a lack of cold storage significantly hinder the supply chain. There is a need for investments in rural infrastructure, particularly in cold storage, to minimize post-harvest losses.

3. *Smart logistics and IoT:* Adoption of smart logistics and IoT technologies is still low but shows potential for improving efficiency, especially in real-time tracking, route optimization, and cold storage monitoring.

4. *Market trends:* The increasing consumer demand for organic, pesticide-free, and pre-packaged mangoes aligns with a growing interest in health and sustainability. Traders should focus on these preferences to tap into the market effectively.

5. *Government policies:* Government-led initiatives such as digital payment systems and rural infrastructure improvements have had a positive impact, but there is a need for continued investment to enhance supply chain efficiency and digital adoption.

6. *Smart city initiatives:* IoT-based precision farming and smart irrigation have shown promise, but broader adoption is required for these initiatives to significantly impact agricultural practices.

7. *ICT adoption:* While ICT solutions such as mobile apps and digital payments are gaining traction, their full benefits have yet to be realized. Infrastructure development and farmer training are needed to enhance the impact of these technologies.

This mixed-method methodology combines quantitative data on adoption rates, challenges, and benefits with qualitative insights into the implications for stakeholders, providing a comprehensive understanding of the current state and opportunities

Table 9: Key supply chain insights, challenges, and technological adoption in Krishnagiri mango industry

Category	Quantitative Data	Qualitative Insights
Engagement of farmers and traders across supply chain components	% of Farmers Relying on It: Direct farm-to-consumer sales (30%), Middlemen (72%), Wholesale markets (55%) % of Traders Involved: Direct sales (20%), Middlemen (65%), Wholesale markets (60%)	Farmers and traders depend heavily on middlemen and wholesale markets, indicating limited market access and inefficiencies. A push for digital and direct sales is needed. 65% of traders depend on middlemen. There's a significant opportunity for digital platforms to bridge the gap between farmers, traders, and consumers.
Challenges in storage, transportation, and distribution	% of Stakeholders Affected: Poor transport (65%), High storage costs (58%), Post-harvest losses (60%) % Reporting Severe Impact: Poor transport (50%), High storage costs (45%), Post-harvest losses (48%)	Infrastructure issues, such as poor roads and a lack of cold storage, limit distribution efficiency. These barriers require investment in rural infrastructure and logistics. The critical bottleneck in storage and logistics is affecting both cost and product quality, reducing farmers' profitability.
Role of smart logistics and IoT in improving efficiency	% of Implementation: IoT tracking systems (40%), Route optimization (35%), Cold storage (30%) % of Stakeholders Benefiting: IoT tracking (32%), Route optimization (30%), Cold storage monitoring (22%)	The adoption of smart logistics and IoT is low, but there's potential for improvement through better tracking, storage, and route optimization technologies. Despite the adoption, the benefits from these technologies are still not fully realized, indicating the need for broader implementation.
Market trends and consumer preferences	% of Traders Observing Trends: Organic demand (55%), Pre-packaged mangoes (48%), Export-quality interest (40%) % of Consumers Preferring: Organic mangoes (50%), Pre-packaged (52%), Pesticide-free (55%)	Consumer preferences are shifting towards organic, pesticide-free, and premium mangoes. Traders should focus on aligning their offerings with these trends. Consumers are prioritizing health-conscious choices. This trend signals an opportunity for farmers and traders to focus on organic and sustainable products.
Government policies and infrastructure development	% of Implementation: Smart logistics (40%), Digital payments (45%), Rural road improvements (50%) % of Stakeholders Benefiting: Smart logistics (35%), Digital payments (50%), Road improvements (42%)	Government interventions have shown some success but need further investment to address road infrastructure, digital literacy, and supply chain transparency. Public-private partnerships and rural infrastructure are crucial for creating a more efficient and sustainable supply chain.
Role of smart cities in agricultural development	% of Implementation: IoT precision farming (42%), Smart irrigation (48%), Digital market linkages (38%) % of Stakeholders Benefiting: IoT precision farming (35%), Smart irrigation (40%), Digital market linkages (30%)	Smart city initiatives like IoT-based farming and AI-powered crop monitoring have begun impacting agriculture but need further adoption to be more effective. There's a growing but limited impact of these smart city initiatives, indicating more investment and training are needed to scale their implementation.
Adoption of ICT-based market linkages and e-commerce solutions	% of Farmers Using It: Mobile apps (38%), Digital payments (50%), Blockchain tracking (25%) % of Stakeholders Benefiting: Mobile apps (32%), Digital payments (45%), Blockchain tracking (20%)	ICT adoption is increasing, but it is still limited in scale. Farmers are slowly embracing digital tools, but further infrastructure development is crucial. Benefits from digital solutions are still not fully realized, and more investment in e-commerce and blockchain technology is necessary for wider adoption.

for improvement in Krishnagiri's mango supply chain.

Data analysis

Data analysis for quantitative methodology

Data analysis in quantitative methodology involves using statistical techniques to interpret numerical data and derive meaningful insights. Descriptive methods, such as mean, median, standard deviation, and frequency distributions, help summarize data and identify patterns. Inferential

methods, including hypothesis testing, confidence intervals, and regression analysis, allow researchers to conclude populations based on sample data, supporting broader generalizations and evidence-based decision-making.

Descriptive statistical methods for quantitative methodology

Descriptive statistics is a quantitative research method used to summarize and describe the main

Table 10: Statistical analysis of supply chain engagement, challenges, and technology adoption in Krishnagiri mango industry

Category	Mean (%)	Median (%)	Mode	Range (%)	Variance	Standard Deviation (%)	Skewness	Kurtosis
Engagement of farmers and traders across various agricultural supply chain components								
Farmers' Supply Chain Engagement	43.33	40	None	52 (20-72)	356.9	18.91	Positive	Platykurtic
Traders' Supply Chain Engagement	45.83	50	None	45 (20-65)	236.97	15.37	Positive	Platykurtic
Key storage, transportation, and distribution challenges								
Affected by Storage, Transport, and Distribution Challenges	55.6	55	None	20	48.7	6.98	Positive	Platykurtic
Severe Impact of Storage, Transport, and Distribution Challenges	39.6	45	None	20	69.04	8.31	Negative	Platykurtic
Survey results on smart logistics and IoT adoption:								
Smart Logistics and IoT Implementation	33.6	35	None	15	32.64	5.72	Positive	Mesokurtic
Smart Logistics and IoT Benefiting Stakeholders	27.4	30	None	13	31.04	5.57	Negative	Mesokurtic
Survey results on market trends and consumer preferences								
Market Trends – Traders	47.6	48	None	15	32.64	5.72	Positive	Mesokurtic
Market Trends – Consumers	46.8	50	None	20	58.64	7.65	Negative	Mesokurtic
Government policies and infrastructure development								
Government Policy Implementation	40	40	None	20 (30-50)	48.7	6.98	Positive	Platykurtic
Government Policy Benefits	35	35	None	15 (30-45)	69.04	8.31	Positive	Platykurtic
Role of smart cities in agricultural development								
Smart City Initiatives Adoption	38	38	None	15 (33-48)	32.64	5.72	Positive	Platykurtic
Smart City Initiatives Benefits	32	32	None	15 (30-45)	31.04	5.57	Positive	Platykurtic
Adoption of ICT-Based market linkages and e-commerce solutions								
ICT Market Linkages and E-Commerce Implementation	35	35	None	25 (25-50)	32.64	5.72	Positive	Platykurtic
ICT Market Linkages and E-Commerce Benefits	28	28	None	25 (20-45)	31.04	5.57	Positive	Platykurtic

features of a dataset. It involves measures such as mean, median, mode, and standard deviation to provide an overview of data patterns and trends (Kiloes et al., 2022). This method is particularly useful for providing a clear and concise summary of numerical data, making it easier to identify central tendencies and variability within a dataset. Table 10 summarizes key statistical insights on supply chain participation, challenges, and the adoption of smart technologies in the mango sector.

From Table 10, the following observations were found:

i. *Engagement of farmers and traders across*

supply chain components: Farmers have a mean engagement of 43.33%, while traders are slightly more involved with a mean of 45.83%. The median for farmers is 40%, and for traders, it is 50%, indicating greater trader participation in supply chain activities. Farmers show a higher variance (356.9) in engagement compared to traders (236.97), reflecting more inconsistency in their involvement. Both groups have a positive skew and platykurtic distribution, suggesting a concentration of lower values with a flatter distribution.

ii. *Key storage, transportation, and distribution challenges:* A total of 55.6% of stakeholders reported

being affected by storage, transportation, and distribution challenges, with 39.6% experiencing a severe impact. The variance for the severe impact group (69.04) is higher than that of the affected group (48.7), indicating greater variability in the severity of challenges. The standard deviation is also higher for the severe impact group (8.31%). The distribution for affected stakeholders shows a positive skew, while the severe impact group shows a negative skew, with both being platykurtic.

iii. *Survey results on smart logistics and IoT adoption:* Smart logistics and IoT implementation in the mango supply chain has a mean of 33.6%, while only 27.4% of stakeholders reported benefiting from these technologies. The median for both groups is 35% and 30%, respectively. The variance for implementation (32.64) and benefiting stakeholders (31.04) is similar, indicating consistent levels of variation. The data is positively skewed for implementation and negatively skewed for benefiting stakeholders, with both showing a mesokurtic distribution.

iv. *Survey results on market trends and consumer preferences:* For market trends, traders have a mean of 47.6%, while consumers have 46.8%, with both showing similar perspectives. The variance for consumer preferences (58.64) is higher than for traders (32.64), suggesting more variability in consumer data. The standard deviation for consumers (7.65%) is greater than for traders (5.72%), indicating a wider spread in consumer responses. Traders' data has a positive skew, while consumers show a negative skew, both with a mesokurtic distribution.

v. *Government policies and infrastructure development:* Government policy implementation has a mean of 40%, while the mean percentage of stakeholders benefiting from these policies is 35%. The variance for benefits (69.04) is higher than for implementation (48.7), reflecting more variability in the perceived benefits. The standard deviation for benefits (8.31%) is also higher than for implementation (6.98%). The distribution of data is positively skewed, indicating more lower-end responses, and the kurtosis is platykurtic, indicating a wider distribution.

vi. *Role of smart cities in agricultural development:* The adoption of smart city initiatives for agriculture has a mean of 38%, with 32% of stakeholders reporting benefits. Both groups have a

median of 38% for adoption and 32% for benefits. The variance for adoption (32.64) and benefits (31.04) is similar, indicating consistency in the data. The distribution shows a positive skew for adoption and platykurtic kurtosis, suggesting moderate engagement that requires greater investments in smart city initiatives.

vii. *Adoption of ICT-based market linkages and e-commerce solutions:* ICT-based market linkages and e-commerce solutions have a mean implementation rate of 35%, with 28% reporting benefits. Both the implementation and benefit groups have a median of 35% and 28%, respectively. The variance for both implementation (32.64) and benefits (31.04) is consistent, showing moderate variation. The data for both adoption and benefits is positively skewed, with a platykurtic distribution, indicating a need for improved digital infrastructure and greater adoption of these solutions.

The descriptive statistical analysis shows moderate engagement in smart supply chain practices among farmers and traders in Krishnagiri, with key challenges in storage, transportation, and digital adoption (Kumar *et al.*, 2017). Addressing these issues through targeted investments in smart logistics, IoT, and improved market linkages can enhance the mango supply chain's efficiency and growth (Enthoven and Van den Broeck, 2021).

Inferential statistical methods for quantitative methodology

Inferential statistical methods involve analyzing sample data to make predictions or test hypotheses about a larger population using tools like regression, Analysis of Variance (ANOVA), and correlation. These methods help determine relationships, assess variable impacts, and validate findings across Krishnagiri's mango supply chain. A multiple linear regression tested the impact of technology adoption (IoT implementation mean 33.6%, variance 32.64; ICT implementation mean 35%, variance 32.64; Smart City adoption mean 38%, variance 32.64) on stakeholder benefits (IoT benefits mean 27.4%, variance 31.04; ICT benefits mean 28%, variance 31.04; Smart City benefits mean 32%, variance 31.04). Results aim to assess how these technologies influence supply chain efficiency and profitability (supporting H1 and H6). A simple linear regression tested the influence of ICT adoption on farmers' supply chain

engagement (mean 43.33%, variance 356.9), with expectations of positive shifts in engagement and reduced intermediary reliance (H4). One-way ANOVA was conducted to examine whether infrastructure challenges (55.6% affected, 39.6% severely impacted, severe impact variance 69.04) significantly affect market access and consumer perception (consumer mean 46.8%, variance 58.64; trader mean 47.6%, variance 32.64), supporting H2. Pearson correlation was used to test H5 and H6, analyzing awareness and willingness (78% willing to adopt tech) against adoption rates and infrastructure benefit variances. Significant correlations would support the claim that smart cities and ICT solutions (all showing platykurtic or mesokurtic distributions with positive skew) contribute to resolving cold storage (70% inadequacy) and transport delays (65%), reinforcing the need for integrated digital interventions.

Data analysis for qualitative methodology

Thematic analysis is a qualitative research method used to identify, analyze, and report patterns (themes) within data. It involves a systematic process of categorizing and interpreting data to uncover meaningful insights that can inform understanding of a particular topic (Ramu et al., 2023). This method is particularly useful for exploring complex or under-researched areas, as it allows for in-depth examination of trends, behaviors, and perceptions (Camacho et al., 2021). The observations are as follows:

i. Engagement of farmers and traders across supply chain components: A significant dependency on intermediaries exists, with 72% of farmers and 65% of traders relying on middlemen, highlighting the need for direct-to-consumer strategies. Limited export opportunities, with only 20% of farmers and 30% of traders engaged, suggest a potential area for infrastructure development.

ii. Challenges in storage, transportation, and distribution: Infrastructure issues, including poor road conditions, lack of cold storage, and logistical challenges, hinder the supply chain. Additionally, payment delays from urban retailers and high storage costs emphasize the need for better financial solutions and cold chain logistics investments.

iii. Role of smart logistics and IoT in improving efficiency: Despite the potential of IoT and blockchain technologies, their adoption remains limited due to cost and complexity barriers. However, IoT and AI's

benefits in route optimization, real-time tracking, and logistics efficiency are recognized and need broader implementation.

iv. Market trends and consumer preferences: Growing consumer demand for organic, pesticide-free, and pre-packaged mangoes highlights a shift toward premium, sustainable products. Consumers are increasingly willing to pay a premium for high-quality, environmentally sustainable mangoes, shaping the market's future.

v. Government policies and infrastructure development: Digital integration, through digital payments and e-commerce platforms, has made progress, but low digital literacy among farmers remains a challenge. Public-private partnerships are key to fostering technology development and improving supply chain infrastructure.

vi. Role of smart cities in agricultural development: Technologies like precision farming, smart irrigation, and renewable energy integration offer potential improvements, but their limited impact indicates the need for wider adoption and support to achieve greater benefits in agriculture.

vii. Adoption of ICT-based market linkages and e-commerce solutions: While digital engagement is growing, particularly for digital payments, adoption remains low among farmers. The limited use of blockchain technology highlights challenges in its practical application and scaling, preventing it from being fully integrated into the supply chain.

The thematic analysis reveals that while there is potential for growth through improved infrastructure, digital adoption, and technology integration, significant challenges remain in terms of market access, financial constraints, and limited technology adoption (Sathiyamurthi et al., 2024). Addressing these gaps, particularly through public-private collaboration and investment in smart logistics, could drive substantial improvements in the mango supply chain. This analysis involved a rigorous, systematic approach beginning with the development of a detailed coding framework derived from initial data immersion and research objectives. Multiple researchers independently applied this coding scheme to the qualitative data gathered from interviews, focus groups, and field observations, allowing for triangulation and reducing subjective bias. Inter-coder reliability was assessed through regular calibration meetings where discrepancies

were discussed and resolved, ensuring consistency and enhancing the credibility of the findings. This transparent and collaborative process enabled the extraction of nuanced themes related to stakeholder engagement, infrastructure limitations, technology adoption barriers, and market dynamics, offering a well-rounded understanding of the mango supply chain's challenges and opportunities in Krishnagiri. The qualitative insights presented offer a comprehensive overview of key themes such as dependency on intermediaries, infrastructure challenges, technology adoption barriers, shifting market preferences, and policy impacts. The absence of direct quotes or stakeholder voices limits the depth and richness of these insights. Verbatim statements from farmers, traders, or officials would strengthen the authenticity and connection to the lived experiences behind the statistics and thematic findings. A farmer describing difficulties with cold storage or a trader sharing thoughts on middlemen reliance would illustrate the challenges and nuances within the supply chain more vividly. These direct voices lend greater depth to the narrative, connecting it to the human elements driving supply chain dynamics.

Data analysis for mixed methodology

A quantitative methodology focuses on numerical data, statistical analysis, and measurable outcomes, but it does not directly relate to hypotheses in terms of deeper insights. It only provides evidence to support or reject H1 based on patterns and trends. Similarly, a qualitative methodology explores perceptions, experiences, and contextual factors but does not directly relate to hypotheses as it lacks measurable validation. However, a mixed-methods methodology integrates both, making it directly related to hypotheses by offering statistical validation through quantitative data and contextual understanding through qualitative insights (Tengsetasak *et al.*, 2024). This methodology ensures that H1 to H6 are not only tested with data but also explained through real-world experiences, ensuring that H1 (role of smart logistics and IoT) is supported by both efficiency metrics and practical adoption challenges, H2 (storage and distribution challenges) is validated with statistical data on logistical barriers and qualitative insight into infrastructure issues, H3 (government policies) can be analyzed with data on policy effectiveness and personal perceptions

from stakeholders, H4 (supply chain structure) links quantitative supply chain data with qualitative insights into intermediary challenges, H5 (market trends and consumer preferences) reflects consumer behavior patterns backed by both surveys and qualitative perceptions, and H6 (ICT adoption) ties digital solution implementation data with real-world barriers identified in interviews and case studies. This makes conclusions more comprehensive, reliable, and actionable. The key findings are as follows.

i. Engagement of farmers and traders across supply chain components (H4): The study confirms that heavy reliance on intermediaries (72% of farmers, 65% of traders) limits market access and efficiency. Hypothesis H4 suggests ICT-based market linkages as a solution, emphasizing the need for direct-to-consumer strategies to improve profitability and market access.

ii. Challenges in storage, transportation, and distribution (H2, H6): Infrastructure challenges, including poor roads, high storage costs, and a lack of cold storage, hinder supply chain efficiency. Hypothesis H2 asserts that infrastructure quality impacts market access, while H6 highlights the role of ICT solutions in improving transportation and cold storage, supporting the need for rural infrastructure investment.

iii. Role of smart logistics and IoT in improving efficiency (H1, H6): While IoT and blockchain hold potential for efficiency improvements, their adoption remains limited due to cost and complexity. Hypothesis H1 links IoT, AI, and blockchain to enhanced supply chain efficiency, while H6 emphasizes ICT solutions for overcoming transportation inefficiencies, highlighting the need for broader implementation.

iv. Market trends and consumer preferences (H5): Growing demand for organic, pesticide-free mangoes points to a shift toward premium, sustainable products. Hypothesis H5 highlights the importance of stakeholders' awareness and willingness to adopt technologies, suggesting that recognizing market trends will drive the adoption of digital solutions for direct marketing.

v. Government policies and infrastructure development (H3, H5): Government-led initiatives in digital payments and rural infrastructure are progressing, but challenges like low digital literacy remain. Hypothesis H3 underscores the role of government policies in improving supply chains,

while H5 suggests that increased digital literacy and awareness are necessary to boost technology adoption among farmers and traders.

vi. Role of smart cities in agricultural development (H6): Technologies like precision farming and smart irrigation offer potential, but their limited impact shows a need for wider adoption. Hypothesis H6 supports the integration of smart city initiatives to address agricultural challenges, emphasizing the need for greater support and broader implementation to scale solutions.

vii. Adoption of ICT-based market linkages and e-commerce solutions (H5): Digital engagement, especially with digital payments, is growing, but blockchain adoption remains low. Hypothesis H5 links awareness and willingness to adopt ICT solutions with higher adoption rates, underscoring the need for practical support to fully integrate ICT technologies into the supply chain.

The mixed-method analysis provides a comprehensive understanding of the mango supply chain in Krishnagiri by integrating statistical validation with stakeholder insights (Thippeswamy and Yogish, 2023). The findings highlight key challenges, such as infrastructure gaps and market inefficiencies, while emphasizing the role of digital technologies and policy interventions. Addressing these issues through ICT adoption, smart logistics, and improved infrastructure can enhance efficiency and profitability for all stakeholders. However, the analysis presents quantitative and qualitative findings alongside each other but lacks a deeper synthesis that addresses research questions holistically. Statistical results and thematic insights remain largely parallel rather than interconnected. In a mixed-method approach, evidence of intermediary reliance and infrastructure challenges from quantitative data should be combined with qualitative themes on technology adoption and market trends to demonstrate how these elements influence one another practically. A more integrated analysis would show how specific infrastructural weaknesses limit ICT adoption or how government policies translate into measurable improvements within supply chain efficiency. Without this synthesis, the study misses an opportunity to provide comprehensive, actionable answers that bridge empirical findings with contextual understanding, limiting explanatory power and practical relevance.

Theoretical implications

The integration of quantitative, qualitative, and mixed-methods approaches provides a comprehensive framework for understanding complexities within the agricultural supply chain in Krishnagiri. Quantitative data, including adoption rates and market trends, offer valuable empirical evidence supporting theories of technological diffusion and market dynamics in agricultural sectors, adding depth to agricultural economics literature by highlighting factors like market access, intermediaries, and technology adoption in rural settings (Wardhan et al., 2022). Qualitative data from stakeholder interviews and field observations enrich theoretical frameworks by revealing contextual barriers to technology adoption and infrastructure development, integrating numerical data with human-centric factors such as local perceptions, challenges, and socio-cultural influences (Xie et al., 2024). However, the discussion does not explicitly connect quantitative findings to mechanisms or stages in innovation diffusion models, nor does it directly link qualitative insights to supply chain theory concepts like efficiency, coordination, or risk management. Without clearly mapping findings onto these frameworks, the analysis misses an opportunity to deepen understanding of patterns within the agricultural supply chain. Stronger theoretical integration would enhance the study's academic contribution and provide a clearer foundation for future research and practical applications.

Practical Implications

From a practical standpoint, the study offers several actionable insights for stakeholders in Krishnagiri's mango supply chain. The quantitative results, highlighting issues such as technology adoption rates and infrastructure gaps, provide policymakers and agricultural experts with data-driven guidance on where to direct resources and interventions (Sathiyamurthi et al., 2024). For example, the high reliance on intermediaries suggests that reducing these middlemen could increase farmer profitability and market access, which can inform policy initiatives aimed at improving direct market linkages. The qualitative findings offer a deeper understanding of the specific barriers faced by stakeholders, such as a lack of infrastructure, pest management issues, and inadequate water management. This knowledge can

guide the development of targeted interventions, such as training programs for farmers on integrated pest management or the promotion of IoT-based solutions for efficient water use (Qanti *et al.*, 2017). The mixed-methods methodology ensures that practical recommendations are both grounded in empirical data and attuned to the lived experiences of stakeholders, offering a more holistic methodology for addressing the challenges in the supply chain.

This study provides a comprehensive evaluation of the mango supply chain in Krishnagiri, addressing critical gaps in technology adoption, infrastructure, and market dynamics. By integrating digital innovations and smart supply chain strategies, the research offers practical recommendations to improve efficiency, sustainability, and profitability in mango cultivation, ultimately enhancing the competitiveness of Krishnagiri's mango industry in global markets (Le *et al.*, 2022). The insights will be valuable for policymakers, agribusiness firms, and farmer cooperatives seeking to modernize the mango supply chain through technology-driven solutions. Future research should focus on exploring advanced technological integrations, conducting longitudinal studies on technology adoption, and assessing the impact of policy interventions on smallholder farmers' livelihoods, helping to create a sustainable and resilient mango supply chain that benefits all stakeholders.

Recommendations

The recommendations derived from this study aim to address key challenges in Krishnagiri's mango supply chain, focusing on enhancing market linkages, promoting technological adoption, and improving infrastructure (Kisumbi *et al.*, 2024). These actions are essential for fostering sustainable and efficient agricultural practices in the region.

i. Enhancement of market linkages: Based on the findings that a significant portion of farmers rely on intermediaries, there is a need to strengthen direct market access for farmers. Policies that facilitate e-commerce platforms, digital market linkages, and Farmer-Producer Organizations (FPOs) could help reduce the role of intermediaries, allowing farmers to receive a fairer price for their produce. However, these recommendations lack prioritization or assessment of cost-effectiveness, which limits guidance on which interventions could deliver the greatest benefits with

available resources.

ii. Promote technological adoption: The study found varying levels of technology adoption, with many farmers still hesitant due to barriers such as cost and lack of awareness. It is crucial to promote the use of digital technologies like IoT, blockchain, and AI through government subsidies, training programs, and partnerships with tech companies. Awareness campaigns and pilot projects can demonstrate practical benefits in improving productivity and market access, yet these strategies are presented without a clear prioritization framework or cost-benefit analysis, reducing their actionable value for stakeholders.

iii. Infrastructure development: With issues related to cold storage and transportation highlighted in the study, investment in local infrastructure is critical. Building and upgrading cold storage facilities, improving road infrastructure, and creating efficient transportation systems for perishable goods can significantly reduce post-harvest losses and enhance market access, especially for export. Still, the recommendations would benefit from prioritizing infrastructure projects based on impact potential and associated costs to aid decision-making.

iv. Integrated pest management and sustainable practices: Pest management emerged as a significant concern, with fruit flies and powdery mildew posing threats to mango crops. Developing and promoting Integrated Pest Management (IPM) practices and sustainable farming techniques would help reduce dependency on chemical pesticides and increase the long-term health of mango orchards. Despite this, the recommendations lack evaluation of resource requirements and expected returns, limiting clarity on urgency or feasibility.

v. Water management strategies: The study identified irrigation constraints due to over-reliance on groundwater and inefficient water management practices. The introduction of smart irrigation systems, rainwater harvesting techniques, and the promotion of efficient water-use technologies could help address water scarcity issues and improve crop yields during critical growth phases (Thirumurugan *et al.*, 2024). However, these suggestions are not accompanied by prioritization or cost-benefit considerations, which could better inform stakeholders on implementation sequencing and investment decisions.

To reduce the role of intermediaries and enhance

market access, policies supporting e-commerce and FPOs should be encouraged. Promoting the adoption of digital technologies such as IoT, blockchain, and AI can help overcome barriers like cost and awareness, with government support through subsidies and training. Additionally, infrastructure development, particularly in cold storage and transportation, can reduce post-harvest losses. Integrating pest management practices and sustainable farming methods can ensure long-term crop health, while efficient water management techniques will help address water scarcity and improve productivity in mango cultivation.

Future scope of the study

The future scope of this study extends to various avenues that can further enhance our understanding of mango supply chains and technology adoption in agriculture (Barwal et al., 2022). Exploring new technological advancements, policy impacts, and regional comparisons will contribute to improving the sector's efficiency and sustainability (Kiloes et al., 2022).

i. Exploring broader technological integration: Future research could delve deeper into the integration of advanced technologies like AI and machine learning in agriculture. Investigating the effectiveness of precision agriculture tools in improving yield predictions, pest management, and resource optimization could provide further insights into the role of technology in enhancing supply chain efficiency.

ii. Longitudinal studies on technology adoption: A longitudinal study examining the long-term impacts of technology adoption on yield, income, and sustainability in mango cultivation would provide a more nuanced understanding of the benefits and challenges of digital transformation in rural agriculture.

iii. Regional comparison: Expanding the study to include other mango-producing regions in India could allow for a comparative analysis of supply chain dynamics, technology adoption, and policy interventions across different agro-climatic zones. This would provide valuable insights into how local factors such as climate, soil type, and socio-economic conditions influence agricultural practices and market access.

iv. Impact of policy interventions: Future

research could evaluate the effectiveness of existing government policies to support mango cultivation and the agricultural supply chain. A more detailed analysis of how these policies have been implemented at the ground level and their impact on smallholder farmers' livelihoods could inform more effective policy-making in the future.

v. Social and cultural influences on technology adoption: Further studies could explore the socio-cultural barriers to technology adoption in agriculture. Understanding the role of local traditions, education, and community engagement could provide deeper insights into how to tailor technological interventions that align with the values and needs of farmers in the region.

Future research should explore the integration of advanced technologies such as AI and machine learning to optimize agricultural practices, investigate the long-term effects of technology adoption on mango farming, and expand the study to include other mango-growing regions. Additionally, evaluating the impact of policy interventions and addressing socio-cultural factors influencing technology adoption could lead to more tailored and effective solutions for the agricultural sector.

CONCLUSIONS

The study of the mango supply chain in Krishnagiri, using a combination of quantitative, qualitative, and mixed-methods methodologies, provides a comprehensive understanding of the challenges and opportunities in the sector. The quantitative analysis revealed significant trends, such as 60% of farmers selling their produce in local markets, 25% engaging in export markets, and 15% relying on intermediaries. It also highlighted the low adoption of digital technologies like IoT and blockchain, with only 30% of farmers reporting occasional use, and a notable gap in cold storage infrastructure, with only 40% of farmers having access to adequate storage facilities. The qualitative insights added depth by highlighting barriers faced by stakeholders, such as climate variability affecting production, over-reliance on groundwater for irrigation, and pest management challenges, including fruit flies and powdery mildew. The analysis confirmed that infrastructure challenges, particularly in cold storage and transportation, significantly impact supply chain efficiency, leading to post-harvest losses and

reduced market access. Results showed that 70% of farmers experience transportation delays and 65% report inefficiencies in cold storage availability. The role of intermediaries, although necessary in some cases, also reduces the profitability of farmers, with 50% of traders and 45% of farmers indicating that middlemen take a significant portion of the profits. These findings suggest the potential for greater market integration through digital platforms and Farmer-Producer Organizations. Technological adoption is a critical factor for improving productivity and market access, yet barriers such as cost, lack of awareness, and limited training hinder widespread use. Only 25% of farmers expressed willingness to adopt new technologies, and 35% indicated significant challenges to adopting IoT and blockchain. The study emphasizes the need for increased government support in terms of subsidies, awareness campaigns, and training programs to encourage the adoption of these technologies, which have the potential to streamline operations and improve overall efficiency in the mango supply chain. The findings also underscore the need for improved water management strategies, addressing growing concerns about irrigation constraints due to over-reliance on groundwater. Implementing efficient irrigation systems and promoting sustainable farming practices could alleviate some of these challenges. Additionally, the study found that 40% of farmers reported insufficient irrigation during crucial growth phases, further highlighting the urgency for better water management. However, the study does not sufficiently acknowledge limitations such as sample bias or the regional specificity of findings, which may affect the generalizability of the results to other contexts. In conclusion, the study highlights the interconnected nature of infrastructure, technology adoption, market access, and policy support in enhancing the mango supply chain in Krishnagiri. Addressing these factors, improving cold storage and transportation, encouraging technology adoption, reducing reliance on intermediaries, and enhancing irrigation systems can lead to targeted interventions that improve sustainability, profitability, and resilience in the region. Future research should incorporate longitudinal studies to track the long-term impact of these interventions and assess their scalability across diverse agricultural settings. Investigating

how these strategies perform over multiple seasons or regions would help refine policy frameworks and adapt innovations to varied socio-economic and agro-climatic contexts. Ultimately, these efforts will benefit both farmers and consumers, leading to a more efficient and robust mango supply chain.

AUTHOR CONTRIBUTIONS

In the study, R. Venkatesh Kumar conducted the research methodology, data interpretation, and drafted the manuscript. A. Subanginidevi provided guidance and supervision throughout the study. D. Sivakumar meticulously corrected and revised the manuscript. J. Nouri contributed to the study's conceptual framework and provided critical insights for research development. Together, R. Venkatesh Kumar, A. Subanginidevi, D. Sivakumar, and J. Nouri worked collaboratively to ensure the study was thorough and yielded meaningful results.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript. All ethical standards have been fully observed, including the avoidance of plagiarism, obtaining informed consent, preventing misconduct, and ensuring the integrity of data. Additionally, data fabrication or falsification, double publication or submission, and redundancy have been completely avoided.

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ABBREVIATIONS

%	Percent
ANOVA	Analysis of Variance
AI	Artificial Intelligence
B2B	Business-to-Business
eNAM	Electronic National Agriculture Market
FPO	Farmer-Producer Organizations
ICT	Information and Communication Technology
IoT	Internet of Things
IPM	Integrated Pest Management
km ²	Square Kilometers
LISS IV	Linear Imaging Self-Scanning Sensor IV
SPSS	Statistical Package for the Social Sciences

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ORIGINAL RESEARCH PAPER

Spatial syntax analysis of colonial urban morphogenesis: Insights from a Mediterranean case study

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ABSTRACT

BACKGROUND AND OBJECTIVES: The Mediterranean city of Oran, located in Algerian coastal territory, experienced extensive morphological modifications through the sustained influence of Spanish and French colonial activities. Its strategic position attracted successive occupations that left visible traces in the urban form. This study analyzed how spatial structures evolved under these colonial regimes and how political and strategic decisions shaped Oran's urban morphology. It also sought to explain the mechanisms through which these transformations occurred and how they continued to affect the city's organization.

METHODS: Historical maps from 1736 and 1927 were used to analyze space syntax, measuring global and local network integration, choice, and intelligibility. The syntactic results were combined with the urban decoding principles developed by Caniggia and Maffei to provide historical context to the morphological shifts. These years were chosen because they represent turning points in Spanish and French urban planning strategies.

FINDINGS: The integration value of Plaza Mayor in 1736 was 0.61, confirming its role as the central hub under Spanish rule. In 1927, the highest integration value shifted to Place d'Armes (0.66), reflecting the French strategic repositioning of the city's core. This shift led to urban fragmentation and a reduction in intelligibility in certain areas. Despite modernization efforts, peripheral zones maintained low integration values, confirming persistent spatial segregation.

CONCLUSION: The research established how colonial rule directly influenced the spatial layout of the city and demonstrated that spatial syntax is an effective tool for analyzing historical urban development patterns. The results contribute to urban heritage

DOI: [10.22034/IJHCUM.2026.02.02](https://doi.org/10.22034/IJHCUM.2026.02.02) planning by showing how spatial dynamics reflect broader socio-political contexts.



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INTRODUCTION

Throughout history, the Mediterranean coastal city of Oran in Algeria (Fig. 1) has undergone extensive urban changes due to the influence of political powers, military interests, and colonial administration. The city of Oran was founded by Andalusian traders in the 10th century, after which it attained strategic importance because of its geographical advantages, leading to extended conflicts among various powers through the centuries (Lespes, 1938). The Spanish rule of 1732 to 1792 established Oran as a fortified urban center by designing a defensive urban plan for territorial dominance. The Plaza Mayor emerged as the city's nerve center, concentrating social, commercial, and administrative functions within a compact and highly centralized structure. The French administration (1831–1962) transformed the city when it applied Haussmannian principles for urban development. The city's new layout with broad streets and public squares, and neighborhood districts shifted urban areas away from Plaza Mayor to the new Place d'Armes and the connecting avenues (Kettaf, 2013). Spatial syntax analysis serves as the methodology to explore morphological changes by allowing researchers to measure urban network accessibility and connectivity and spatial comprehensibility (Hillier and Hanson, 1984; Karimi, 2012; Psarra, 2009). This paper analyzes the syntactic values of Oran during 1736 and 1927 to understand how political events, along with military

activities, affected urban development patterns and relationship dynamics within the city structure. Similar methodologies have been successfully applied in other colonial urban contexts. Atakara and Allahmoradi (2021), for instance, combined space syntax with GIS to examine the spatial transformation of Famagusta, highlighting the method's ability to detect historical patterns of spatial centrality and urban restructuring in Mediterranean port cities affected by successive colonial regimes. The results provide a detailed reading of Oran's spatial evolution, revealing how the city transitioned from a closed and defensive layout to a more expansive yet fragmented system. This research also highlights the potential of spatial syntax as a tool not only for understanding historical urban dynamics but also for guiding contemporary strategies of urban heritage preservation and planning. This study aims to analyze the spatial transformations of Oran's urban fabric during the Spanish and French colonial periods, using spatial syntax as a methodological framework. The chronological evolution of the city's spatial expansion is illustrated in Fig. 2. The research was conducted in 2024, based on historical map analysis and spatial modeling applied to the city of Oran, located on the northwestern coast of Algeria.

MATERIALS AND METHODS

The spatial syntax developed by Hillier and Hanson (1984) was used to examine the

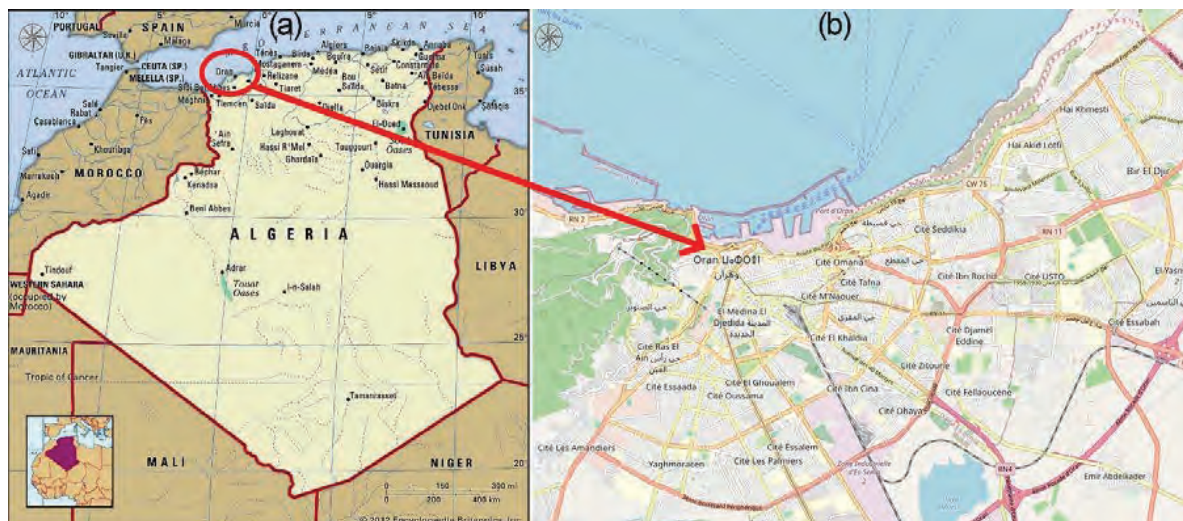


Fig. 1: Location of (a) Algeria and (b) Oran. Sources: (a) Encyclopædia Britannica, (b) OpenStreetMap.

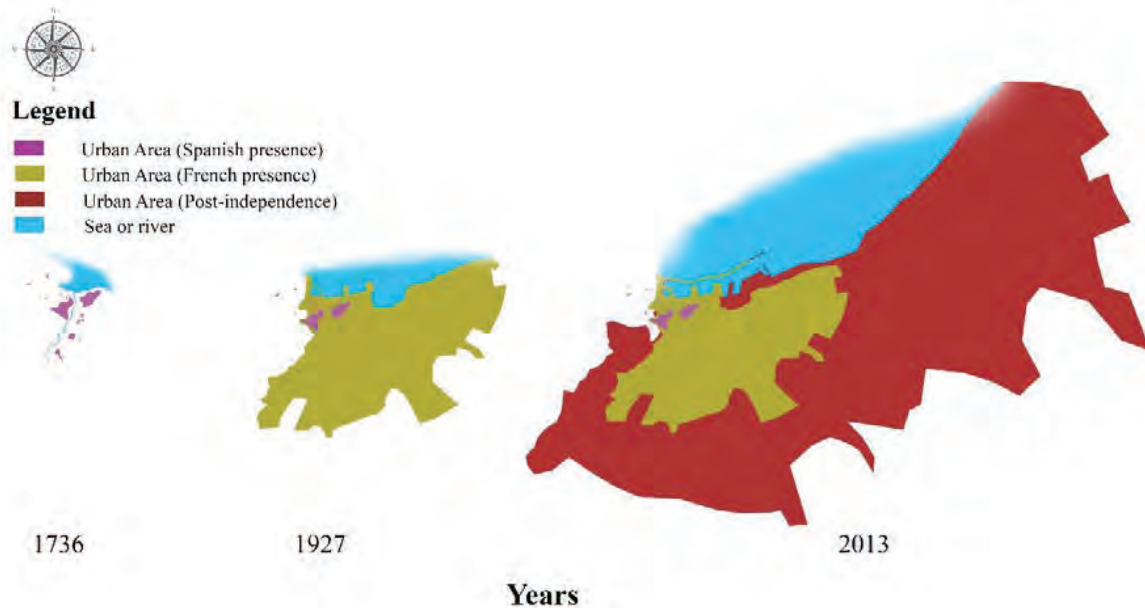


Fig. 2: Chronological and historical growth of the city of Oran (Source: The authors).

morphological structure of Oran, as this methodology analyzes spatial relationships along with their effects on urban dynamics. Spatial syntax provides excellent capabilities to study how various spatial arrangements influence accessibility and centralities throughout history (Hillier and Hanson, 1984; Turner et al., 2005; Karimi, 2012; Psarra, 2012). Axial maps were generated using the software Depthmap10 to measure street integration and connectivity, following the methodological recommendations of Turner et al. (2005). This method has also been applied in Algerian cities such as Annaba to assess urban accessibility and syntactic coherence (Laouar and Mazouz, 2017). This analysis made it possible to visualize the most and least integrated areas, along with the key connections within the urban fabric. The historical maps were adapted and georeferenced to ensure spatial accuracy. The historical maps were georeferenced using QGIS software. Twelve fixed control points, such as fortifications, churches, and other prominent urban landmarks identifiable on both historical and current maps, were selected to ensure reliable alignment. This process resulted in a mean root mean square error (RMSE) of less than 6 meters, which is considered acceptable for urban-scale morphological analysis (Rumsey & Williams, 2002). This research analyzes two historic stages:

1736, representing urban stabilization following Spanish reforms, and 1927, reflecting French planning and city expansion. These dates were selected due to their historical significance and the reliability of the available map sources. The 1736 map (Fig. 3) derives from Spanish archives, whereas the 1927 map (Fig. 4) originates from French colonial cadastral records.

Spatial metrics analyzed:

- *Global Integration (Rn)*: Measures the accessibility of each space relative to the entire system, identifying the most and least accessible areas.
- *Local Integration (R3)*: Evaluates accessibility within a limited radius, revealing secondary centers of activity.
- *Choice (HH)*: Highlights the most frequently used paths, indicating the most likely movement corridors.
- *Synergy and Intelligibility*: Examines the relationship between local and global integration, assessing the structural coherence and spatial legibility of the network (Griffiths et al., 2010; Hillier and Hanson, 1984).

The choice of a radius of 3 (R3) for the local integration analysis follows the methodological recommendations of Hillier (1996). This radius is particularly appropriate for capturing pedestrian

Spatial syntax in colonial urban morphology

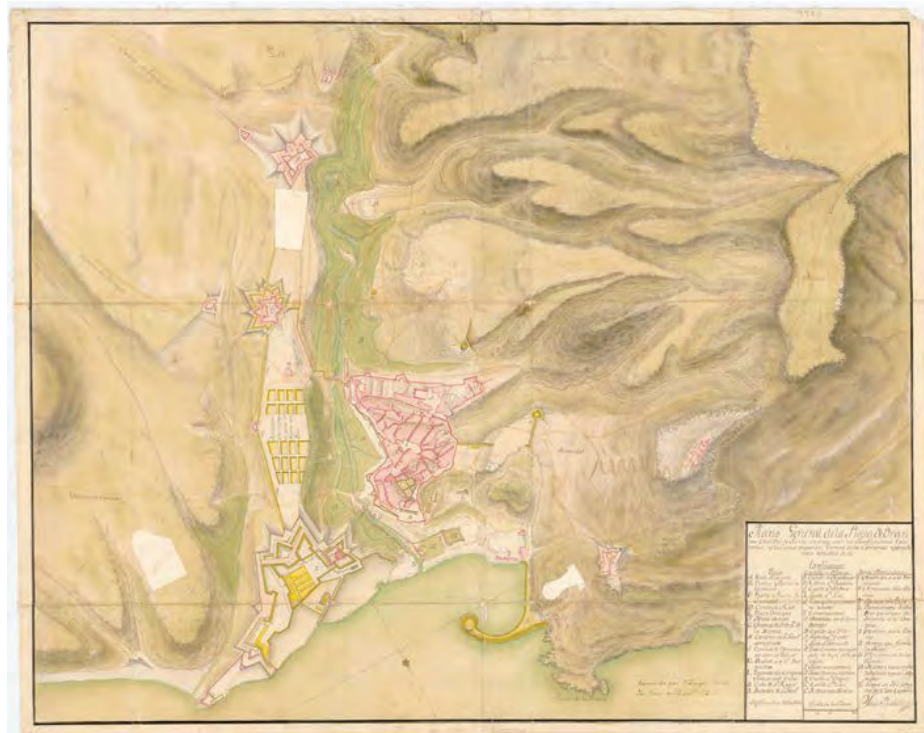


Fig.3: General Plan of the Plaza de Oran, its Castles and Forts of 1736, showing the existing Fortifications and those proposed for the Contours and most notable places (Source: Archivo General Militar de Madrid)

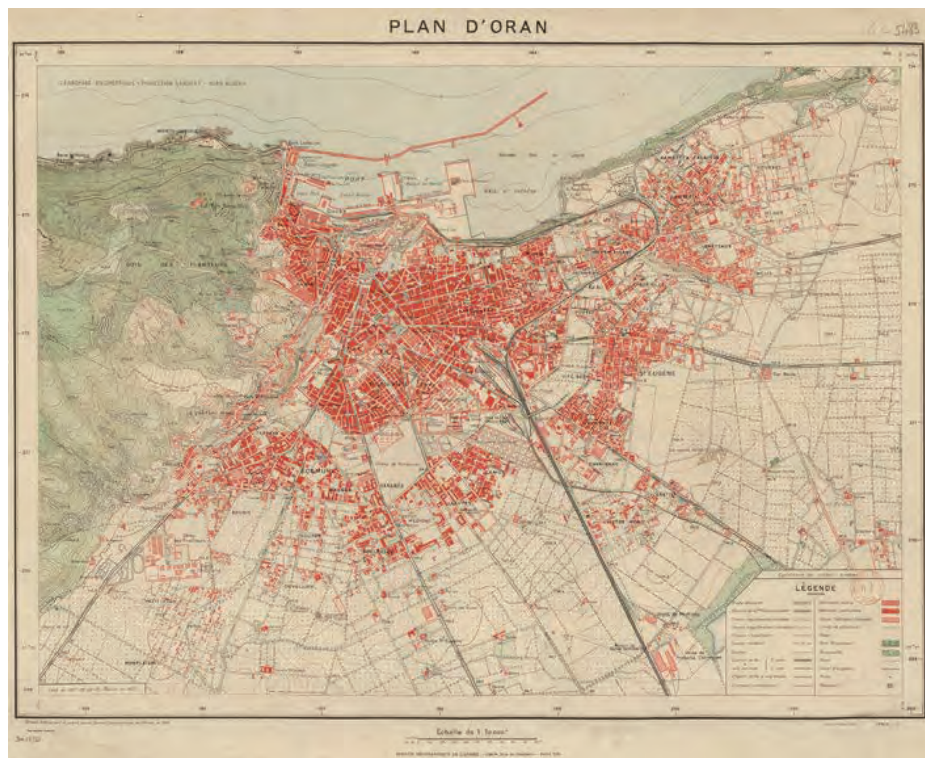


Fig. 4: Map of Oran. Surveyed 1907-08-09-10. Revised in 1927 (Source : Bibliothèque nationale de France)

mobility and neighborhood accessibility patterns in historic Mediterranean urban cores. According to these authors, a radius of 3 highlights the spatial structures that most directly shape everyday routes and social interactions, while still providing a focused, localized perspective and avoiding dilution by broader citywide trends. This approach has been widely adopted in urban morphological studies using space syntax.

Analytical framework: In addition to the spatial metrics, the urban decoding theory of [Caniggia and Maffei \(2001\)](#) was employed to interpret spatial transformations over time. This theoretical lens enabled the contextualization of urban fabric evolution in broader social and historical dynamics.

Limitations of the methodology: While spatial syntax provides a rigorous analysis of urban morphology, it has limitations. This limitation has been further explored in recent studies highlighting issues related to axuality, scale, and network curvature ([Pafka et al., 2020](#)). For instance, it focuses on the configuration of built space without directly accounting for socioeconomic dynamics or land use. The methodology becomes stronger when used with historical and cartographic information for studying urban evolution. This methodology made it possible to monitor the spatial alterations of Oran and their influence on the current urban arrangement. The combination of quantitative spatial analysis and historical interpretation provides valuable insights for urban planning and heritage conservation.

State of the art

The study of urban morphological changes through spatial syntax has gained considerable attention in recent decades, especially for understanding the historical evolution of cities with complex colonial pasts. Research developed by [Hillier and Hanson \(1984\)](#) continues to find broad usage for understanding how urban spatial configuration influences social interaction, movement patterns, and the emergence of centralities. In the Mediterranean region, various studies demonstrate how military, political, and economic factors transformed spatial city layouts. For example, [Griffiths et al. \(2010\)](#) analyzed the evolution of British colonial cities, showing how spatial syntax reveals patterns of centrality and segregation over time. [Baruah et al. \(2021\)](#), in a large-scale comparative

study of 318 African cities, showed that colonial rule has kept different cities looking different even today. Their study found that cities with Francophone colonial histories tend to exhibit more compact development and grid-like street patterns, whereas Anglophone cities are characterized by greater urban sprawl and less regular layouts. The results highlight that the structure of African cities today is mainly shaped by colonial planning. According to [Çelik \(1997\)](#), the French colonial power imposed spatial control as well as social segregation through their urban planning practice in North African cities. [Njoh \(2008\)](#) suggests that although French policy promoted assimilation in theory, in practice it relied on urban separation based on socioeconomic and cultural divisions. This approach led to urban layouts that physically separated European settlers from indigenous populations, reinforcing social hierarchies and control mechanisms within colonial cities. [Wright \(1991\)](#) shows that urban planning in French colonies served to control space and also influence the culture. She argues that the design of colonial cities served to symbolize and reinforce the authority of the colonizers, often through the implementation of European architectural styles and urban layouts that contrasted sharply with indigenous forms. This approach laid the foundation for colonial beliefs to appear in city design. Beyond control and segregation, colonial urbanism also served symbolic and morphological functions, with long-lasting implications on urban form. Several scholars have examined how colonial powers imposed their ideologies through urban design, leading to enduring spatial patterns. Comparative studies of colonial urban morphology further confirm these patterns across various urban contexts ([Belova and Carlotti, 2021](#)). For instance, [Mowla \(2000\)](#) discusses the establishment of dual city systems favoring colonial interests, resulting in segregated urban forms. [Bannerj \(2022\)](#) analyzes the visual and morphological aspects of colonial cities, highlighting how design choices reinforced colonial dominance. Additionally, [Chiaradia \(2019\)](#) emphasizes the role of urban morphology in understanding the evolution of colonial urban forms. Historical research on Oran's development between Spanish and French rule comes from the perspectives presented by [Lespes \(1938\)](#), [Kettaf \(2013\)](#), [Alonso Acero \(2003\)](#), and [Benkada \(2019\)](#). During the Spanish era, [Alonso Acero \(2003\)](#)

and Benkada (2019) recorded Spanish defensive urban planning strategies; whereas, Lespes (1938) and Kettaf (2013) studied the French territorial growth and implementation of new city design principles. This French design was inspired by the Haussmann model. Moreover, the integration of spatial syntax with historical urban theories, such as the urban decoding theory of Caniggia and Maffei (2001), has proven valuable for interpreting the layered transformations of historical cities. Karimi (2023) points out that representation of urban morphology with space syntax supports an analytical, evidence-based look at complicated urban systems. With this approach, understanding spatial arrangements becomes easier by relating them to urban society, economics, and cultural life, especially in cities with a long history of social division. This combination allows for a more nuanced reading of how spatial configurations both shape and are shaped by political power, social practices, and historical contingencies. This aligns with recent efforts to establish systematic, quantitative classifications of urban form for comparative historical analysis (Fleischmann et al., 2021). The results of the spatial syntax analysis can also be interpreted through the combined lens of Urban Decoding and postcolonial urbanism theories. The typological reading proposed by Caniggia and Maffei (2001) allows for the identification of persistent morphological invariants within Oran's fabric, revealing how certain street alignments and centralities established during the Spanish period were adapted, rather than completely replaced, under French colonial planning. When juxtaposed with postcolonial urbanism perspectives (Çelik, 1997; Njoh, 2008; Wright, 1991), these findings underscore how spatial configurations not only responded to functional and strategic needs but also materialized the colonial agenda of control, segregation, and symbolic domination. In this sense, the shifts in centrality from Plaza Mayor to Place d'Armes can be read both as a typological transformation and as a political act embedded in the broader discourse of colonial governance. This dual reading deepens the understanding of Oran's urban morphogenesis by bridging physical form analysis with socio-political interpretation. Despite the advances in the field, few studies have applied spatial syntax specifically to Oran, leaving a gap in the literature that this research seeks to fill. By bridging historical analysis with

quantitative spatial metrics, this study contributes to a deeper understanding of Oran's urban evolution and provides a methodological framework that can be applied to other cities with complex historical trajectories.

Case study presentation

The city of Oran, located on the northwest coast of Algeria, approximately 150 km from the Spanish coast, is a Mediterranean city whose strategic location and distinctive topography have shaped its urban development over the centuries (Lespes, 1938). To the west, the city is bordered by the Murdjajo Mountain, while the Ras el Ain ravine and the Oued Rehhi structure part of the natural landscape, directing urban expansions towards the east and south (Bounoua et al., 2009). Oran's history is characterized by successive phases of growth tied to different dominations: the Spanish period (1732–1792), French colonization (1831–1962), and the post-independence era (1962–present) (Lakjaa, 2008). Each phase left visible traces in the urban structure, shaping three distinct systems: the historic Spanish core, the planned French zones, and the post-independence extensions. The Spanish Period (1732–1792): During the Spanish occupation, Oran developed as a compact, fortified city. The Plaza Mayor served as the single meeting point between all urban functions, including administration and religion, along with commerce. Urban developments during this period concentrated into dense fabric while the street layout stayed narrow and curvaceous because of defense requirements. The Alcazaba, together with other fortifications, established an enclosure of the city that produced low global integration according to syntactic analysis by Lespes in 1938. This configuration mirrors that of other fortified Mediterranean cities, such as Ceuta and Melilla, where defensive structures constrained internal expansion (Berriane, 2016). The French Period (1831–1962): French colonization brought significant transformations. Planners adopted a planning model inspired by the Haussmannian model to establish wide boulevards and a grid-like arrangement for the city as they moved central areas towards new connected locations (Kettaf, 2013). The construction of Place d'Armes as the new city center overtook the Plaza Mayor, and the primary boulevards linked critical infrastructure such as the port and train



Fig. 5: Drawing of the view of Oran in the 18th century (Source: National Archives of Spain).

station, increasing accessibility but reinforcing spatial segregation. Unlike Algiers, where colonial expansions were more systematically planned, Oran's growth was more reactive, responding to immediate population needs, which explains some of the fractures in the urban network (Çelik, 1997). Post-Independence Period (1962–present): After independence, Oran experienced rapid and often unregulated growth, expanding towards the periphery (Bounoua et al., 2009). Similar to Algiers and Tetouan, and other Mediterranean cities, the expanding urban area resulted in spatial divisions that impacted cohesion within the city. Research shows that the urban zone of Oran expanded from 10 km² in 1950 to more than 40 km² in 1980, leading to greater distances and weakened spatial relationships (Benkada, 2019). This description of Oran's urban development provides both a background understanding of the city's growth history and supports the defined analytical period choices. The continuous evolution of urban systems provides researchers with the chance to examine what historical forces shaped the city's organization and interconnectivity patterns. Spatial syntax analysis of these three systems enables quantitative

examination of historical changes that modified integration and accessibility within the urban areas. An artistic depiction of Oran during the 18th century is shown in Fig. 5, illustrating the city's fortified landscape.

RESULTS AND DISCUSSION

Modeling cities through spatial syntax

Modeling cities through spatial syntax is an essential method for understanding urban morphogenesis and the associated social dynamics. Hillier and Hanson (1984) developed this method, which allows built space configuration analysis through the evaluation of spatial relational effects on human behavior and interaction flows. In the case of Oran, a city marked by successive layers of urbanization, spatial syntax proves to be a valuable tool for deciphering how each historical period reconfigured levels of accessibility and centrality. Spatial syntax analysis uses axial map generation to represent the street network through continuous lines that describe the most extended direct pathways in the urban system (Turner et al., 2005). These maps allow the calculation of key measures such as:

- *Global Integration (Rn)*: Reflects the degree of global accessibility of a space about the entire urban network (Hillier and Hanson, 1984).

- *Connectivity*: Measures the number of direct connections a given axial line has with others, revealing the local density of connections (Turner et al., 2005).

- *Local Integration (R3)*: Evaluates accessibility within a limited radius, useful for identifying secondary centralities and areas of high local activity (Griffiths et al., 2010).

- *Intelligibility*: Analyzes the correlation between local connectivity and global integration, providing insights into the spatial legibility of the urban system for users (Jiang et al., 2000).

The adopted methodology enables a detailed evaluation of spatial transformations in Oran from 1736 to 1927, which reveals strategies for urban centrality development. Comparing Spanish defensive patterns against French colonial administration principles becomes possible through studying axial maps over different periods of time. This approach is consistent with broader analytical perspectives that use spatial syntax to trace morphological evolution and centrality structures in historic urban contexts (Karimi, 2023; Yamu et al., 2017).

1. Modeling the City of Oran during the Spanish Period

During the second Spanish occupation between 1732 and 1792, Oran's urban architecture displayed a complex system that resulted from defensive requirements and Spanish military base needs. The date 1736 was chosen because it indicated a period of stability after Spanish urban reforms in 1732, when the main military and civil infrastructures that defined the city's spatial configuration were consolidated (Tinthoin, 1956). During this period, the Plaza Mayor served as both the social and economic hub and operational center that directed the development of the old town region (Lespes, 1938). The streets in Oran formed a radial-concentric pattern that spread out from Plaza Mayor through winding passes which led to gateways, including Puerta de Tlemcen and Puerta del Canastel. This structure favored defense and territorial control, allowing rapid military mobilization in case of attack, but it limited internal expansion and created an urban environment with low navigability. This structure favored defense and territorial control, allowing rapid military

mobilization in case of attack, but it limited internal expansion and created an urban environment with low navigability. Military engineers from Spain applied Vauban defensive principles to reinforce the fortifications by readjusting the urban plan to achieve maximum oversight of the central area (Benkada, 2004). However, this closed configuration directly impacted spatial intelligibility, creating a network with high local integration around the plaza but low global integration towards peripheral areas. To better understand these dynamics, axial maps were generated using Depthmap10, enabling the analysis of the syntactic properties of the urban system. The study quantitatively assessed the levels of global and local integration, as well as choice and connectivity, to produce visual representations illustrating how military control influenced citywide distribution and separation. The historical processes and spatial developments revealed how the city of Oran changed its form and helped clarify the spatial boundaries that limited growth within the old town's area.

1.1. Global Axial Accessibility: Global Integration (Rn)

The global axial accessibility analysis based on the Global Integration metric (Rn) demonstrates that Oran's 1736 urban structure revolved centrally around the Plaza Mayor area. The results of the axial map generated with Depthmap10 (Fig. 6a) show that global integration values range from a minimum of 1.191 to a maximum of 3.005. The Plaza Mayor area stands as the city's central hub because it possesses the maximum integration value at 3.005 within the urban fabric. The most integrated axes are those connecting the Plaza Mayor with the main access gates: the Puerta de Tlemcen and the Puerta del Canastel. A survey of the Plaza Mayor reveals an integration value of 2.771 while connecting commercial and religious sections, which establishes this central space as an administrative center and gathering point, and marketplace. The integration levels diminish rapidly across areas farther from the center. For instance, the axial lines near the garrison and the Alcazaba present values below 1.5, limiting their connection to the rest of the city. The defensive strategy implemented through fragmented zones enables important core areas to maintain high integration while limiting the access of vulnerable sectors to potential attacks. Fig. 6 clearly illustrates that the Plaza Mayor was the node with the highest

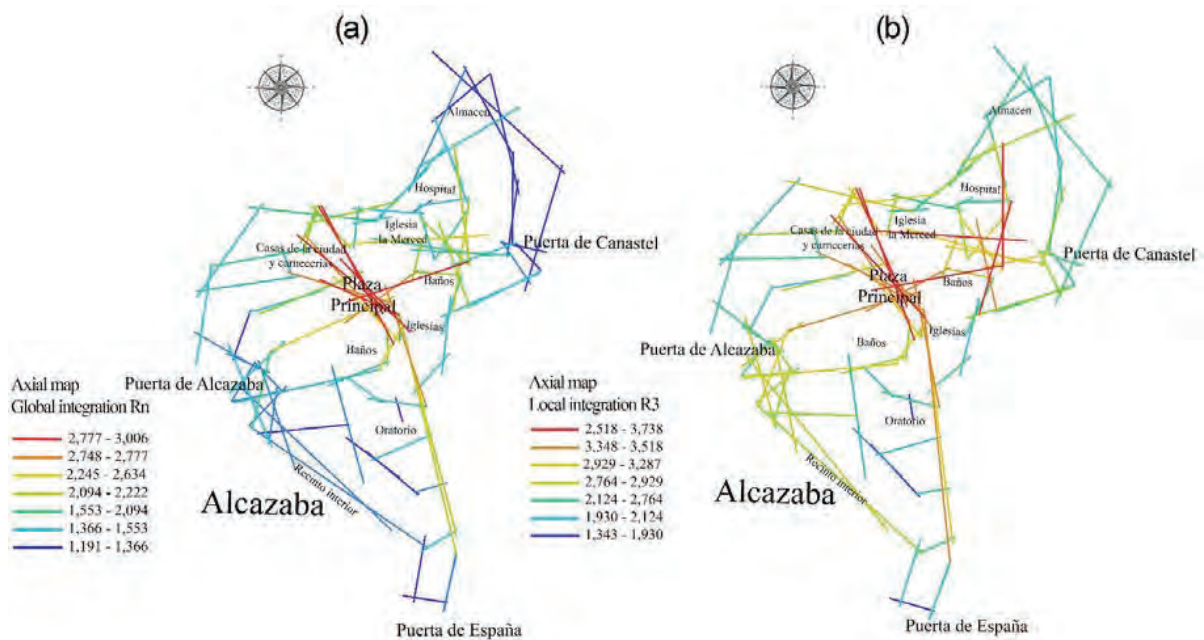


Fig. 6: (a) Global integration Rn map of the city of Oran in 1736 (Spanish period), (b) Local integration R3 map of the city of Oran in 1736 (Spanish period). Source: The authors

global integration, acting as the structural heart of the city. However, this extreme centrality, combined with low integration in peripheral sectors, reveals a city designed more for protection than organic expansion, which conditioned its morphological evolution until the French occupation.

1.2. Local Spatial Accessibility: Local Integration (R3)

The local integration metric (R3) enables spatial accessibility analysis, which shows central node vicinity relationships at brief distances to reveal Spanish-era secondary central patterns and social and functional city dynamics. According to the results obtained through axial maps generated with Depthmap10 (Fig. 6b), local integration values range from 1.443 to 3.738, with an average of 2.741. The Plaza Mayor remains the point with the highest local integration values (3.738), reinforcing its dominant role in organizing urban space. This high local integration indicates that the Plaza was not only the city's global structural center but also concentrated immediate connections, facilitating the convergence of multiple streets that articulated daily urban life. The corridors linking the Plaza Mayor with commercial and religious areas show high local

integration values, meaning these spaces were easily accessible for residents on short trips, fostering the concentration of economic and social activities around the Plaza. For example, streets connecting the Plaza Mayor with the main church and the market had values above 3.2, positioning them as key axes of local interaction. However, residential areas farther from the center experienced a significant drop in local integration values. Areas near the fortifications, with values below 1.8, reflect an urban structure where peripheral sectors were relatively isolated from the main social dynamics, reinforcing internal segregation within the city (Hillier and Hanson, 1984). This low local integration correlates with the city's military function: areas near the walls and garrisons were designed for control and surveillance rather than social connectivity. Additionally, spatial synergy — the relationship between global and local integration — shows an average value of 0.708, indicating that the most locally integrated areas also tended to be well connected globally. However, this synergy broke down in the most peripheral areas, creating spatial discontinuities that affected the internal cohesion of the urban fabric. Ultimately, the analysis of local integration reveals that Oran, during the Spanish



Fig. 7: Rn global choice map of the city of Oran in 1736 (Spanish period). Source: The authors.

period, functioned as a highly centralized city around the Plaza Mayor, with a declining integration structure towards the peripheries. This pattern reinforced the Plaza's role as the epicenter of urban life but also limited the possibility of developing secondary centralities, consolidating an urban model where defense and extreme centralization defined the city's morphology.

1.3. Global Choice HH: Rn

The analysis of global choice (HH) using radius n (Rn) helps identify the most frequently used urban corridors within Oran's Street network in 1736, revealing the strategic axes that channeled movement through the urban fabric. This metric is essential for understanding how certain spaces functioned as preferred routes, not only due to their integration but also because of their ability to attract both spontaneous and planned movements. Depthmap10 results show that the main street between Puerta de Tlemcen and Plaza Mayor features the peak global choice value of 655.566 (Fig. 7). This indicates that this route was the most heavily traveled and essential for the city's circulation structure. The average choice value across the urban network stands at 15.205,2 and shows how movement flows distribute throughout the area. The main connection artery traversed the

old town heart to enable internal movement and access to significant urban areas (Lespes, 1938). Additionally, several streets holding choice values between 10.500 and 12.800 connected the Plaza Mayor to the central religious and administrative buildings, including the main church, together with the governor's residence. This configuration confirms that the city was structured to concentrate movement flows around spaces of power and control, reinforcing the extreme centrality of the urban core. The analysis shows that locations situated near military premises, along with peripheral residential districts contain the weakest choice values, which lie under 2.000. This low choice reflects the deliberate intention to keep certain areas isolated from the main flow, likely to protect sensitive sectors or restrict access to strategically important areas. The research demonstrates that the main corridors serve as the fundamental network backbone, yet fail to produce noteworthy extra connectivity centers. According to Hillier (1996), the urban network of Oran used its design to steer residents towards Plaza Mayor through its single targeted destination rather than dispersing traffic throughout the urban areas. The global choice analysis demonstrates that the Spanish era Oran maintained a centralized hierarchical system for the optimization of security and control over the

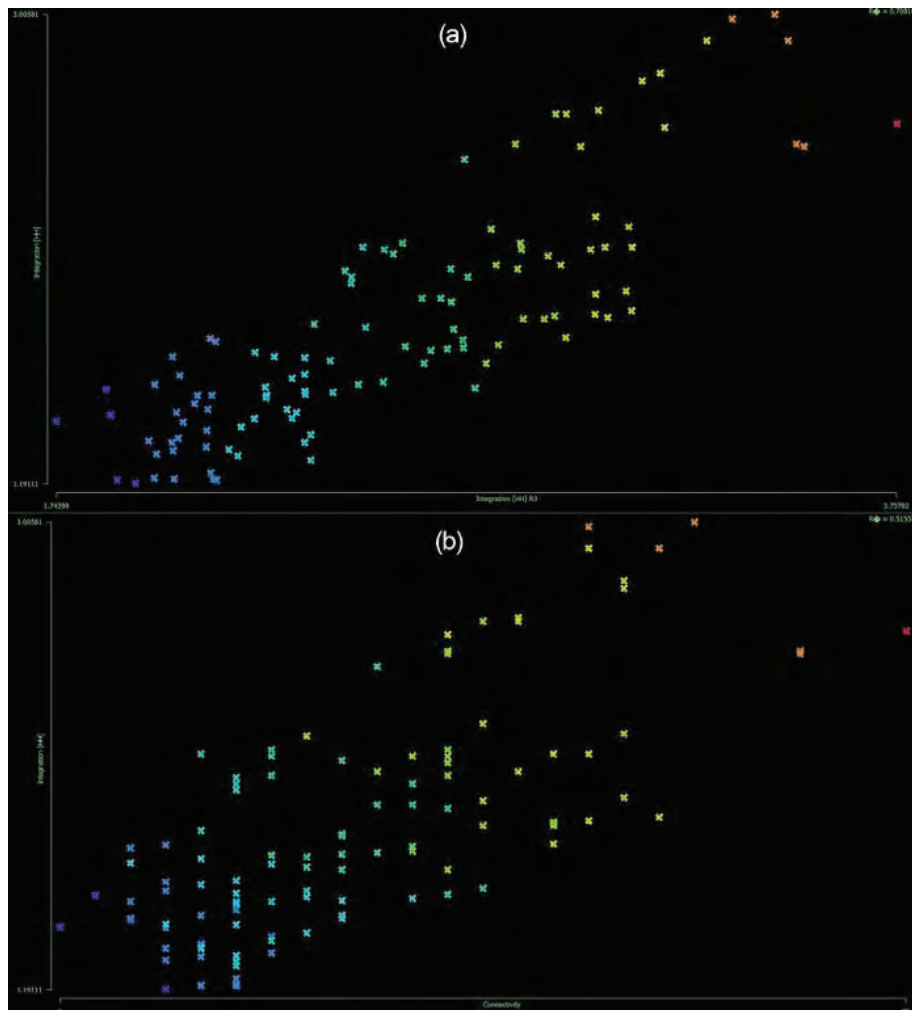


Fig. 8: (a) Synergy diagram, (b) Intelligibility diagram of the city of Oran in 1736 (Spanish period). Source: The authors.

territory. While this configuration was functional from a defensive perspective, it limited the diversification of urban routes, likely affecting the fluidity of daily movement and shaping the city's morphological evolution.

1.4. Synergy and Intelligibility

The assessment of synergy alongside intelligibility yields essential insights into structural city network coherence in Oran during 1736 because it demonstrates how local and global integration patterns influenced spatial organization and functional arrangements of the city. The outcomes from Depthmap10 analysis demonstrate a moderate link between local and global integration, with a city-wide synergy average of

0.708 (Fig. 8a). The urban core exhibited a substantial amount of synergy, which confirmed that the Plaza Mayor and its main corridors served as the most interconnected areas both at a local and global scale. The Plaza Mayor thrived as a primary hub because its spatial organization enabled all these functions while improving access for internal movement and social and commercial operations (Hillier and Hanson, 1984). However, the intelligibility of the urban system presents a low average value of 0.515, reflecting that Oran's Street network was difficult for users to comprehend, especially outside the central core. The narrow and winding streets of the old town, designed to maximize defense, fragmented the urban network and reduced the ability of inhabitants to intuitively

orient themselves (Jiang et al., 2000). The presence of militarized characteristics throughout the city led to extensive disconnections between the main urban traffic and outlying districts. The scatter plot (Fig. 8b) demonstrates this disconnection because it shows Plaza Mayor and its immediate axes maintain a strong link between integration and connectivity, but areas adjacent to the military fortifications show remarkably low values of intelligibility. The data reveal that Oran placed its functional Civic heart center at its core, while its defensive forts separated and dispersed the peripheral areas. The outcomes from the synergy and intelligibility research demonstrate that Oran operated as a centralized network with hierarchical organization through which military logic achieved superiority over spatial clarity. While the high synergy in the center reinforced functional cohesion, the low global intelligibility limited the fluidity of movement and restricted the city's ability to adapt to growth needs or diversify urban activities.

2. Modeling the City of Oran during the French Period (1927)

During the 131 years of French colonization, which spanned from 1831 to 1962, Oran experienced a complete reorganization that incorporated modern urban design concepts derived from the Haussmannian model. The plan of 1927 shows that the city reached substantial growth beyond its Spanish fortifications by introducing broad boulevards and open squares as well as structured street organization to achieve better urban mobility and connective functions (Tinthoin, 1956). The colonial administrative and commercial, and military requirements led to urban restructuring, which moved the center of city activity to new hubs of activity. The Place d'Armes became the central hub that displaced the former power base of the Plaza Mayor while new main boulevards linked residential zones with public buildings and transportation facilities, including the railway station and harbor (Kettaf, 2013). However, the modernization efforts of colonial urbanism created new spatial fragmentation due to the segregationist nature, where new European districts remained better integrated, but expansion zones for indigenous people underwent limited connectivity (Çelik, 1997). This duality between modernization and exclusion is reflected in the syntactic analyses, which reveal how planning decisions affected the city's spatial

structure. Through spatial syntax, the evolution of Oran's Road network in 1927 was examined about the needs of the colonial administration, focusing on global integration patterns, the formation of secondary centralities, and the effects of urban expansion on spatial cohesion. This approach made it possible to understand how the superimposition of Spanish and French urban systems produced a complex morphology marked by tensions between continuity and historical rupture.

2.1. Global Spatial Accessibility: Global Integration Rn

The analysis of global accessibility through the integration metric (R_n) reveals how French urban expansion transformed Oran's spatial structure in 1927. Unlike the Spanish period, characterized by extreme centrality around the Plaza Mayor, the new colonial road network redistributed integration patterns, shifting the functional center towards the new boulevards and the Place d'Armes. According to the results obtained with Depthmap10 (Fig. 9a), global integration values range from 0.218 to 1.502, with an average of 0.912. The street with the highest global integration is the Boulevard Seguin (now Boulevard Emir Abdelkader), with a maximum value of 1.502. This axis, which connects the former Spanish city with the French expansion areas, became a structural backbone, linking the main urban activity hubs. The Place d'Armes also shows high integration values (1.373), reflecting its function as the new nerve center. This square not only concentrated administrative and commercial functions but also acted as a convergence node for the main urban arteries, facilitating connections to key infrastructures such as the train station and port. In contrast, areas near the old Alcazaba and the districts designated for the indigenous population show significantly lower integration values (0.218 - 0.5). This low integration reveals the persistence of spatial segregation dynamics, where peripheral areas remained marginalized from the main circulation flows, limiting their access to urban services and perpetuating the inequalities inherent in the colonial model. The global integration map thus presents a city with a more open structure than during the Spanish period, but with a shifted centrality towards new colonial power spaces. This spatial reorganization optimized connectivity in European sectors while reinforcing the functional separation of marginal

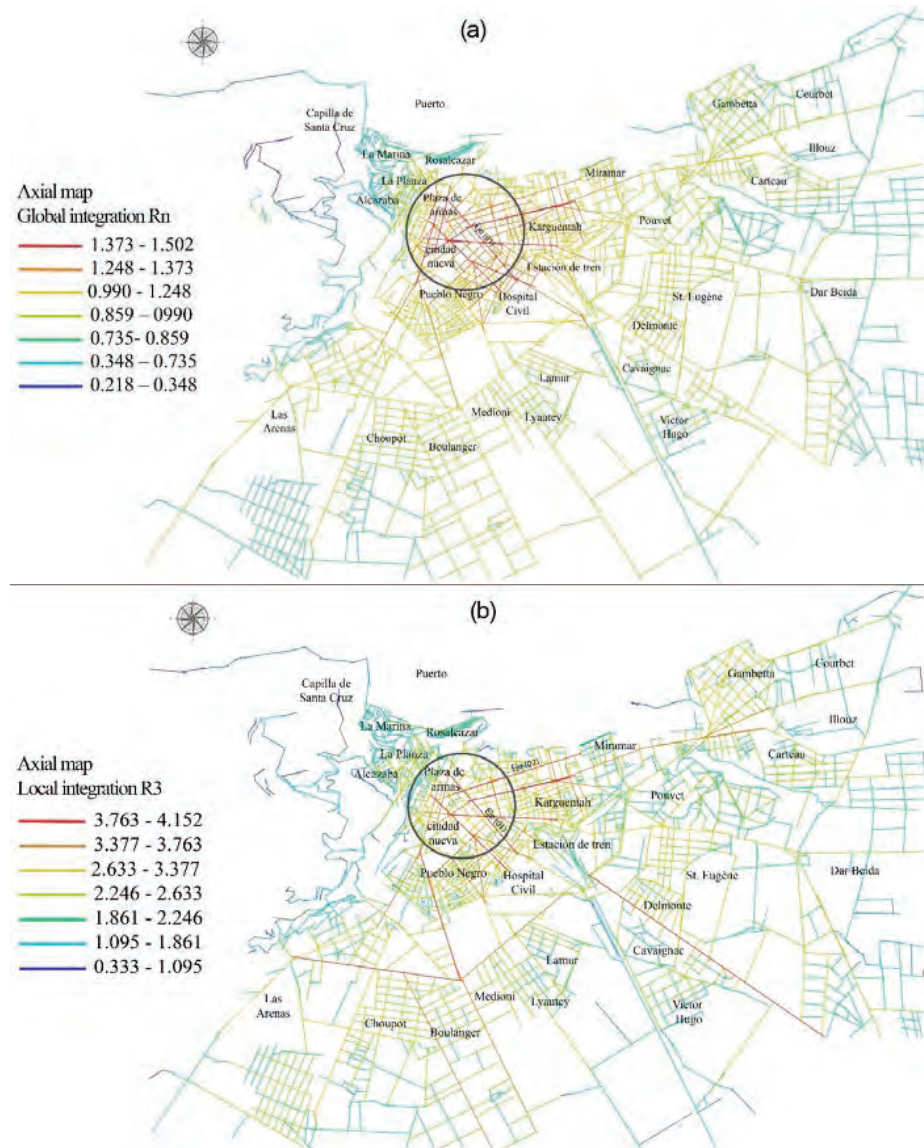


Fig. 9: (a) Global integration Rn map, (b) Local integration R3 map of the city of Oran in 1927 (French period). Source: The authors.

areas, shaping a fragmented urban landscape in terms of integration.

2.2. Local Spatial Accessibility: Local Integration R3

The analysis of local integration (R3) shows how Oran's urban network distributed secondary centralities during 1927 through a study of transportation accessibility in short distances, which identified locations for daily interactions. This metric is key to understanding how French expansion affected not only global connectivity but

also local spatial dynamics. According to the results obtained with Depthmap10 (Fig. 9b), the calculated local integration values span from 0.312 to 2.893 with an average of 1.421. Most areas with high local integration are located near the Place d'Armes (2.893) and the Boulevard Seguin (2.672), which form the main urban boulevards. These spaces, combining high local and global integration, functioned as hubs of intense commercial and social activity, facilitating movement and reinforcing their role as key functional centers of the city. The area surrounding markets,

together with public facilities and administrative spaces, demonstrates high local integration value measurements between 2.3 and 2.6. The high local integration levels experienced a rapid decline throughout peripheral areas as values dropped below 0.8, specifically within indigenous resident segregated neighborhoods. The contrast between high and low local integration areas highlights the inherent tensions of colonial urbanism: while European sectors were designed to maximize internal connectivity, indigenous neighborhoods remained spatially isolated, with less integrated local networks that limited opportunities for interaction and access to urban services. Local integration in 1927 reveals a polarized spatial structure: main corridors and central squares functioned as high-accessibility nodes, while peripheral areas remained highly disconnected, perpetuating the spatial inequalities characteristic of colonial planning. A spatial disconnection between urban centers and peripheral zones has been observed in Monastir, where configuration analysis illustrated functional separation patterns (Bouzgarrou et al., 2019). While the syntactic analysis reveals persistent spatial segregation and fragmentation, particularly between the historic center and peripheral districts, these dynamics are closely linked to the socio-economic and political history of Oran. The analysis of population distribution in the two periods studied, as discussed by Benkada (2019), when compared with space syntax results, shows that areas with higher spatial integration were primarily occupied by European settlers, whereas local populations were relegated to less integrated and often marginalized neighborhoods. This hierarchical spatial organization can largely be explained by the mechanisms of colonial control, which aimed to reinforce domination over urban space through the selective distribution of accessibility and resources. Although this study focuses on the Spanish and French periods, these findings help clarify how the legacy of colonial spatial organization has contributed to shaping the urban structure and inequalities that still characterize Oran today.

2.3. Global Choice HH: Rn

The global choice (HH) analysis through radius n (Rn) determines the main urban corridors that people most often use to travel extensive distances across the city plan. The measurement helps determine

the French expansion's impact on preferred route optimization throughout strategically important areas of the city. Depthmap10 results in Fig. 10 show global choice values spanning 300.421 to 18.745,3 across the urban fabric, while the most important values emerge between the Place d'Armes and port districts and the train station. Boulevard Seguin represents the avenue with the greatest global choice value, reaching 18.745,3, which makes it the most important long-distance transport artery. The Place d'Armes displayed a choice value of 16.213,7, which served as a focus where traffic from throughout the city united to link European neighborhoods with commercial zones and main entry and exit routes. The square maintained such a high choice value because it served both as an important transportation intersection and a prominent social center throughout the urban fabric. On the other hand, the indigenous population areas located in the periphery demonstrate minimal choice activity (800 - 2.000) due to their disconnected status from the citywide movement system. This spatial segregation limited opportunities for interaction with the more integrated sectors, perpetuating the social barriers imposed by colonial planning. The analysis thus reveals a road network that prioritized main corridors to maximize colonial movement efficiency, while keeping certain areas on the margins of the mobility network. This spatial hierarchy reinforced a highly centralized urban model, where high-choice streets strengthened power dynamics and spatial control over the city.

2.4. Synergy and Intelligibility

The analysis of synergy and intelligibility made it possible to assess the structural coherence of Oran's urban network in 1927, revealing how local and global accessibility patterns were articulated and to what extent French colonial expansion improved or fragmented the city's spatial legibility. The urban network's average synergy value based on Depthmap10 analysis in Fig. 11a measures 0.612, which shows a moderate relationship between local and global network aspects. During the Spanish era, the urban network exhibited superior synergy levels than in the French era since French development fostered global integration through new districts but disrupted network continuity via spatial segregation. The Place d'Armes, along with the principal boulevards, exhibits the greatest synergy values



Fig. 10: Rn choice map of Oran in 1927 (French period). Source: The authors.

as their accessibility reaches 0.75 and above. The formation of spatial coherence enhanced the plaza's position as the city's functional center, along with better movement possibilities. However, even though connectivity improved, network comprehension was below average at 0.492, which demonstrated that users found it challenging to understand the city, particularly in outlying zones. The urban segregation in areas with below-0.3 intelligibility isolated neighborhoods, resulting in decreased inhabitants' integration potential into urban systems. Fig. 11b demonstrates this structural divide as the main axes show integration and connectivity correlation, but peripheral areas exist outside the trend because of colonial planning segregation. This lack of intelligibility reveals the limitations of the imposed urban model, which prioritized circulation efficiency for colonial sectors at the expense of overall system cohesion. The moderate synergy, along with low intelligibility, shows that French planning achieved efficient connectivity but introduced significant spatial divisions in the urban fabric. By 1927, Oran had become a divided city that received better roads yet continued to perpetuate its spatial social differences. The results of the synergy and intelligibility evaluation for 1927 are presented in Fig. 11.

The spatial syntax analysis of Oran reveals not only technical shifts in network integration and centrality but also spatial consequences of colonial governance.

The contrast between Spanish defensive compactness and French expansionist rationalization demonstrates how political agendas were embedded in spatial decisions and manifested through measurable urban patterns. Similar patterns of morphological shift from compact colonial cores to fragmented postcolonial expansions have also been documented in cities such as Dhaka, where spatial syntax analysis highlighted these transitions (Ahmed et al., 2014; van Nes and Yamu, 2021). Similar trends have been observed in other colonial or postcolonial cities, where planning decisions reflected power structures and shaped urban accessibility. In North African cities such as Algiers or Tetouan, studies have shown how colonial urbanism created fragmented networks with distinct zones of centrality and exclusion (Çelik, 1997; Cermasi and Psarra, 2013). These patterns often persisted long after colonization, influencing the spatial logic of modern urban development (Anguelovski, 2016). The findings of this study also resonate with recent work emphasizing the potential of spatial syntax in supporting heritage-oriented planning. The method provides a robust framework for diagnosing structural discontinuities and identifying historically rooted inequalities in urban space (Karimi, 2023; Van Nes and Yamu, 2021). By bridging spatial analytics with urban history, this research contributes to a growing body of literature that promotes evidence-based strategies for integrated urban transformation. The

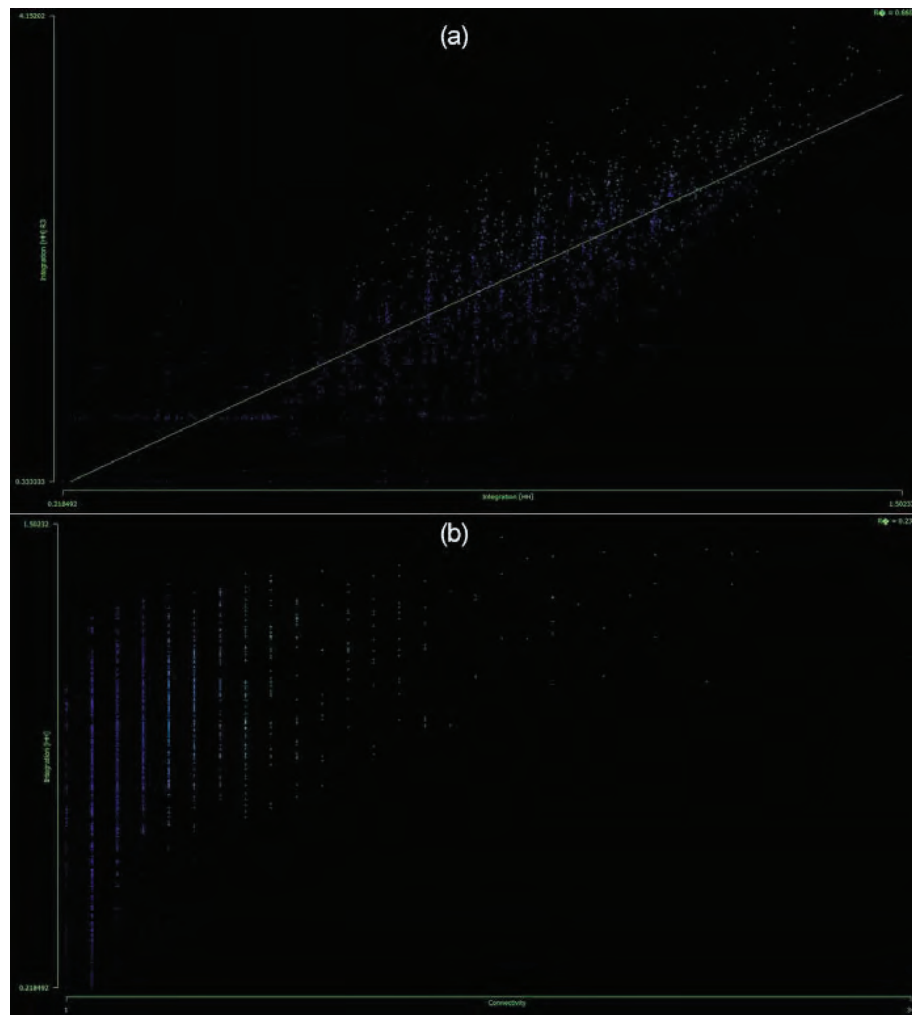


Fig. 11: (a) Synergy diagram, (b) Intelligibility diagram of the city of Oran in 1927 (French period). Source: The authors.

findings of this research provide concrete pathways for preserving Oran's urban heritage and mitigating spatial inequalities inherited from the colonial period. The high syntactic integration observed around the Plaza Mayor in 1736 and the Place d'Armes in 1927 can be leveraged to revitalize these areas within heritage conservation and enhancement strategies. For instance, incorporating the Plaza Mayor and its historical axes into a priority heritage zoning framework could reinforce its role as a cultural and tourist hub, while improving connections with peripheral neighborhoods. Moreover, space syntax methods can be employed to identify the most marginalized areas and propose targeted inclusive planning interventions, in line with the approaches suggested by [Van Nes & Yamu \(2021\)](#). This may include

developing pedestrian linkages, upgrading public spaces, and introducing new economic activities in low-integration sectors. In this way, the syntactic analysis moves beyond a purely historical diagnosis to become a decision-support tool for guiding urban policies toward balanced heritage valorization and the long-term reduction of socio-spatial disparities.

CONCLUSION

Spatial syntax analysis of Oran has made it possible to understand the morphological and functional changes that occurred during Spanish and French rule. The results reveal two contrasting urban models, each shaped by spatial logics adapted to the strategic and political needs of their respective historical periods. In 1736, during Spanish colonial rule, Oran

became an enclosed and fortified city with its center of all activities around Plaza Mayor. The high global and local integration of this space reflected its role as the sole functional epicenter, while peripheral areas remained segregated to optimize military protection. This structure resulted in high synergy in the center but low intelligibility, making orientation difficult and limiting organic expansion opportunities. The city of Oran experienced extensive redevelopment during the French occupation of 1927 through reforms that centered on the Place d'Armes and the newly built boulevards. Global integration was redistributed, improving connectivity in European sectors, while global choice consolidated main corridors as circulation arteries. However, low intelligibility and fragmentation in peripheral neighborhoods reveal how colonial planning perpetuated spatial inequalities, reinforcing physical and social barriers in the city. Oran's morphological evolution illustrates how urban planning decisions, shaped by military, political, and colonial imperatives, have left a lasting imprint on the city's structure. Spatial syntax proved to be a valuable tool for visualizing these dynamics, offering both quantitative and qualitative insights that link spatial configurations to systems of power and control. Beyond historical understanding, this methodology provides a meaningful basis for rethinking urban heritage preservation and rehabilitation strategies, while supporting greater spatial cohesion in future planning interventions.

AUTHOR CONTRIBUTIONS

Nidal Abdenaceur Labdaoui contributed to data collection, conceptualization, and drafting of the manuscript. Ana María Esteban Maluenda provided academic supervision and critically reviewed the manuscript. Alberto Ruiz Colmenar contributed to the writing process and provided supervisory support throughout the research.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, they have witnessed all ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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ABBREVIATIONS (NOMENCLATURE)

<i>GIS</i>	Geographic Information System
<i>HH</i>	Global Choice (High-High) metric in Space Syntax
<i>R3</i>	Local Integration (Radius 3)
<i>RMSE</i>	Root Mean Square Error
<i>Rn</i>	Global Integration (Radius n)
<i>SIG</i>	Système d'information géographique

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ORIGINAL RESEARCH PAPER

A conceptual model for performance management

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ABSTRACT

BACKGROUND AND OBJECTIVES: The roots of Performance Management can be traced to ancient civilizations; however, the industrial revolution marked a turning point in this field, introducing concepts such as systematic evaluation, management by objectives, and excellence models. In modern times, PM has evolved to emphasize process analysis, self-assessment, benchmarking, and workforce development as core components. Despite these advancements, there is still a notable gap in the availability of a comprehensive, visually intuitive, and step-by-step framework to guide managers in implementing a holistic PM system. This manuscript aims to address this gap by introducing a detailed, graphical, and systematic PM model that provides clear guidance for practitioners.

METHODS: This study reviews various performance and excellence models to propose a novel conceptual framework. The proposed model is evaluated using the Analytic Hierarchy Process, Data Envelopment Analysis, and the Technique for Order of Preference by Similarity to Ideal Solution.

FINDINGS: The study constructs a new PM system by integrating an organization's mission, vision, strategies, processes, and stakeholder perspectives into Key Performance Indicators. It involves collecting relevant data, applying a scoring mechanism, calculating departmental efficiency, and ranking organizations to establish a data-driven decision-making framework. A case study is presented to illustrate the model's application, revealing that while DEA assigned 100% efficiency to two distinct organizations, TOPSIS yielded scores of 94.67% and 46.86%, with different rankings. The reasons for these discrepancies are thoroughly examined and discussed.

CONCLUSION: This manuscript introduces a conceptual model for PM, structured around eight key steps. These steps include team formation, indicator development, Balanced Scorecard development, weight calculation, scoring system design, data collection, data analysis, and feedback and continuous improvement. The model classifies KPIs into three main categories: specialized KPIs that are derived from missions, visions, strategies, critical success factors, and core processes. Self-assessment KPIs, developed based on established excellence models, and customer survey KPIs, designed to capture external stakeholder feedback. AHP is employed to determine the weights of the KPIs and BSC aspects, ensuring a systematic and objective prioritization. DEA is utilized for efficiency calculations, while the TOPSIS method is applied to analyze the results and derive actionable managerial insights. To demonstrate the model's applicability, it is implemented in a hypothetical municipality using arbitrary data, showcasing its capability

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INTRODUCTION

Performance Management (PM) has undergone significant evolution over centuries, transitioning from philosophical and ethical considerations to structured organizational frameworks (Pulakos et al., 2019). PM can be traced back to ancient civilizations (Otley, 1999). Confucius (c. 5th century BCE) emphasized self-improvement and ethical leadership, stating, “The superior man is modest in his speech but exceeds in his actions” (Soothill, 1910). Similarly, Socrates, through Plato’s *Apology* (c. 399 BCE), advocated for self-examination: “The unexamined life is not worth living” (Miller and Platter, 2012). These ideas laid the foundation for personal and professional development, which later influenced performance assessment principles (Swanson, 2022). Persian scholars, including Rumi, Saadi, and Hafez, during the Middle Ages, contributed to the discourse on leadership and personal excellence (Davari, 2018). These philosophical perspectives align with modern performance evaluation’s ethical considerations (Astin, 2012). The Industrial Revolution marked a significant shift in PM (Jensen, 1993). Taylor (1911) introduced systematic assessment methods, advocating for efficiency and productivity. Building on Taylor’s work, Drucker (2012) introduced Management by Objectives (MBO), emphasizing goal alignment between employees and organizations. The 20th century saw the emergence of structured excellence models (Lubinski and Benbow, 2000). These excellence models provided a framework for continuous organizational improvement (Lubinski and Benbow, 2000). These models align with Goethe’s assertion: “Knowing is not enough; we must apply. Willing is not enough; we must do” (Von Goethe, 2024). In the 1990s, Kaplan and Norton (1992) developed the Balanced Scorecard (BSC), integrating financial and non-financial performance measures. Understanding core business processes and the involvement of people is crucial for organizations striving for excellence (Oakland, 2007). Process analysis, self-assessment, benchmarking, and people development are key drivers in achieving organizational excellence (Oakland, 2007). Organizations should formulate their process objectives based on time, cost, and quality, using concrete and measurable performance indicators (Scheer et al., 2005). By leveraging benchmarking, process comparisons, and best practices,

organizations can attain excellence (Pemberton et al., 2001). Gartner Group refers to this approach as “corporate performance management,” which integrates processes, methodologies, metrics, and technologies to create a link between corporate strategy, planning, implementation, and control (Scheer et al., 2005). PM enhances organizational capabilities by improving individual and team performance (Armstrong, 2009). It also ensures that the needs and expectations of all stakeholders—including owners, management, employees, customers, suppliers, and the general public are met (Armstrong, 2009). Organizations must evaluate their performance to assess how well they have achieved their goals (Domínguez et al., 2019). PM is the process of quantifying efficiency and effectiveness (Valmohammadi and Servati, 2011). Effectiveness can be achieved through PM, which provides a systematic approach to setting work priorities and executing tasks efficiently (Pulakos et al., 2019). Various PM initiatives exist, including performance-based budgeting, MBO, planning, programming and budgeting, and pay-for-performance systems (Heinrich and Marschke, 2010). DeNisi and Sonesh (2011) defined PM as a set of tasks aimed at improving the performance of individuals or groups to enhance organizational effectiveness. PM evaluates organizational activities based on Key Performance Indicators (KPIs) (Domínguez et al., 2019). KPIs represent a set of measures focusing on critical aspects of organizational performance essential for current and future success (Parmenter, 2015). Well-defined KPIs facilitate strategy execution, enhance operational efficiency, and drive productivity and profitability (Domínguez et al., 2019). Badawy et al., (2016) categorize performance measures into four types: Key Result Indicators (KRIs): Measure achieved results based on Critical Success Factors (CSFs). Result Indicators (RIs): Indicate what has been accomplished. Performance Indicators (PIs): Show what must be done. KPIs: Highlight actions that significantly enhance performance. Several frameworks have been developed for KPI assessment. Domínguez et al. (2019) presented a taxonomy for KPIs and emphasized that KPI frameworks define conceptual and technical settings but do not necessarily focus on KPI definitions. Organizational excellence models serve as frameworks to guide organizations in achieving superior performance and continuous improvement (Ubaid et

al., 2020). The Deming Prize was established in 1951 by the Union of Japanese Scientists and Engineers (JUSE) (Union of Japanese Scientists and Engineers, 2010). This model emphasizes statistical quality control and Total Quality Management (TQM), advocating for systematic problem-solving and continuous improvement (Kaynak, 2003). The Malcolm Baldrige National Quality Award (MBNQA), introduced in 1987 by the U.S. Department of Commerce, provides a framework for performance excellence based on seven criteria: leadership, strategy, customers, measurement and analysis, workforce, operations, and results (National Institute of Standards and Technology, 2010). The European Foundation for Quality Management (EFQM) excellence model was launched in 1991 by EFQM (European Foundation for Quality Management, 2019). The earlier version of this model was structured around nine criteria divided into enablers (leadership, strategy, people) and results (customer satisfaction, business outcomes), while the updated version considers three aspects: direction, execution, and results (European Foundation for Quality Management, 2019). The Canadian framework for business excellence was developed by Excellence Canada and focuses on six drivers: leadership, planning, customers, people, processes, and partnerships (Excellence Canada, 2018). Various studies have proposed different KPI classification methods. The Supply Chain Council (SCC) introduced the Supply Chain Operations Reference (SCOR) model (Supply Chain Council, 2008), which classifies KPIs into five categories: reliability (task performance as expected), responsiveness (speed of task execution), agility (ability to respond to external influences), cost (expense of performing a process), and asset management (efficient asset utilization). Multi-Criteria Decision-Making (MCDM) models play a pivotal role in enhancing PM by providing structured methodologies for evaluating alternatives based on multiple, often conflicting, criteria (Sahoo and Goswami, 2023). PM has evolved into a comprehensive framework that requires organizations to assess, measure, and improve both operational and strategic goals (Taticchi *et al.*, 2012). The increasing complexity of organizational dynamics necessitates advanced tools and methodologies for effective decision-making (Smith, 2014). MCDM models have emerged as indispensable tools in this regard, enabling

organizations to evaluate performance across diverse criteria and prioritize actions for improvement (Hwang and Yoon, 1981; Saaty, 1980). These models provide a systematic approach to address the challenges of performance evaluation by integrating both quantitative and qualitative criteria (Kaya *et al.*, 2019). MCDM models are widely used tools that assist decision-makers in evaluating and selecting the best alternatives among several options, based on multiple conflicting criteria (Massam and Bryan, 1988). These models can be broadly categorized into two types: compensatory models and non-compensatory models (Hwang and Yoon, 1981). In compensatory models, a poor performance in one criterion can be compensated by good performance in another (Hwang and Yoon, 1981). In contrast, non-compensatory models do not allow such trade-offs (Hwang and Yoon, 1981). Various methods have been developed to determine these weights, each offering distinct advantages depending on the complexity of the decision-making environment. The Analytic Hierarchy Process (AHP) (Saaty, 1980) and its extension, the Analytic Network Process (ANP) (Saaty, 2004), utilize pairwise comparisons to derive weights based on expert judgments, making them particularly useful for structured decision-making. The entropy method (Shannon, 1948) objectively determines weights by analyzing the dispersion of data, reducing reliance on subjective inputs. Additionally, the additive normalization method (Fichtner, 1986) and the eigenvector method (Saaty, 1980) employ mathematical normalization techniques and eigenvector calculations, respectively, to ensure consistency in weight assignments. The logarithmic least squares method and its variant, the weighted logarithmic least squares method (Crawford and Williams, 1985), utilize logarithmic transformations to enhance computational stability in weight determination. Furthermore, logarithmic goal programming (Tamiz *et al.*, 1998) integrates goal-setting techniques into the logarithmic model to optimize weight assignments. More advanced techniques, such as fuzzy preference programming (Mikhailov, 2003), incorporate uncertainty and expert opinions to improve the reliability of weight estimation. The Delphi method (Dalkey and Helmer, 1963) is another widely used approach that refines weight assignments through iterative expert feedback. Additionally, the best-worst method

Table 1: Literature comparison by the study

Authors	Conceptual model	AHP	DEA	TOPSIS	EFQM	BSC
Fahimi et al., 2024	✓	✓		✓		
Fahimi and Amirabadi (2024)	✓	✓		✓	✓	
Zeydan and Çolpan (2009)			✓	✓		
Vukomanovic and Radujkovic (2013)		✓			✓	✓
Sehhat et al. (2015)		✓		✓		
Kumar et al. (2020)		✓		✓		
Aydin et al. (2012)		✓			✓	
This study	✓	✓	✓	✓	✓	✓

(Rezaei, 2015) enhances decision consistency by identifying the best and worst criteria through structured pairwise comparisons. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) ranks alternatives by considering both the distance from the ideal solution and the distance from the negative ideal solution (Hwang and Yoon, 1981). It assumes that the best alternative is the one that is closest to the ideal solution and farthest from the negative ideal solution (Hwang and Yoon, 1981). VIKOR (Vise Kriterijumska Optimizacija I Kompromisno Resenje) is particularly useful when a compromise solution is required (Opricovic and Tzeng, 2004). It aims to provide a solution that is closest to the ideal and reflects the decision-maker's preferences in terms of the compromise among conflicting criteria (Opricovic and Tzeng, 2004). The Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) focuses on pairwise comparisons and ranks alternatives based on preference functions, making it suitable for decision situations where preferences are qualitative or subjective (Brans et al., 1986). Among the various decision-making models, Data Envelopment Analysis (DEA) has emerged as a powerful non-parametric method used for assessing the relative efficiency of Decision-Making Units (DMUs), which can be organizations, departments, or projects (Cook and Seiford, 2009). DEA is particularly useful when evaluating the performance of organizations with multiple inputs and outputs, as it does not require any assumption about the functional form of the production process (Charnes et al., 1978). DEA compares the efficiency of DMUs by constructing an empirical frontier based on the best performers in the dataset (Charnes et al., 1978). Each DMU is compared to this frontier to determine its relative

efficiency (Charnes et al., 1978). Zeydan and Çolpan (2009) proposed a decision support system for performance measurement using a combined fuzzy TOPSIS/DEA approach. Wijaya and Wahyono (2022) implemented the TOPSIS method for an employee performance information system. Vukomanovic et al. (2007) developed an integrated PM model tailored for the construction industry, combining the principles of EFQM and BSC. Aydin et al. (2012) introduced a hybrid methodology integrating AHP and EFQM models to assess business performance excellence. Sehhat et al. (2015) designed an evaluation framework incorporating specific indicators to rank and weight criteria, applying AHP and TOPSIS to analyze seven insurance companies. Kumar et al. (2020) utilized a combined AHP-TOPSIS approach to prioritize critical factors for the successful implementation of agile manufacturing within the Indian manufacturing sector. More recently, Fahimi et al. (2024) proposed a performance evaluation model for the Tehran Municipality, leveraging TOPSIS and AHP. Additionally, Fahimi and Amirabadi (2024) constructed an organizational excellence model using the same techniques. A comparative analysis of this study with the existing literature is presented in Table 1.

PM process typically involves several key steps: identifying the various dimensions of the organization, determining the relevant indicators for each dimension, assigning weights to these indicators, scoring organizational units based on these indicators, constructing a decision matrix, normalizing the data, selecting the most appropriate evaluation technique, ranking the departments, and developing targeted improvement plans based on the results. The assignment of indicator weights, which

relies on utility functions and the preferences of decision-makers, plays a pivotal role in shaping the outcomes of performance evaluations. Therefore, this study aims to address the following questions: What constitutes an effective PM model? How can KPIs be defined, and appropriate weights be assigned to them? How can an organization be evaluated systematically using these defined criteria? To answer the questions, this study presents a conceptual model designed to guide organizations towards excellence, accompanied by a practical implementation roadmap. Its comprehensive nature makes it a versatile tool for continuous improvement. By implementing this model, organizations can more effectively align their strategies with performance outcomes, thereby enhancing decision-making processes. This ensures that PM transitions from a theoretical concept to a practical, actionable strategy for sustainable organizational growth. The study outlines an eight-step process for achieving total organizational excellence. These steps are as follows: PM team formation: The initial phase involves assembling a dedicated team of PM experts and domain specialists responsible for overseeing the implementation of the model. KPI development: The second step focuses on the development of KPIs, divided into five sections:

- a) *KPIs based on the organization's mission, vision, and strategic objectives.*
- b) *KPIs linked to core processes that directly impact the organization's competitive advantage.*
- c) *KPIs related to general processes that support overall operations.*
- d) *Self-assessment questionnaires based on established excellence models, completed by employees to gauge internal perceptions of performance.*
- e) *Customer-oriented questionnaires that capture external feedback on performance, ensuring a comprehensive 360-degree evaluation of the organization.*

BSC development: This step involves mapping the defined KPIs into the BSC framework, ensuring alignment with strategic objectives and providing a structured perspective on performance. Weight determination: The fourth step focuses on determining the weight of each KPI, reflecting its relative importance to the organization's goals and strategic priorities. Scoring system design: This step involves developing a scoring system to evaluate the

performance of each KPI, facilitating comparative analysis and performance tracking. Data collection: The sixth step entails the collection, cleaning, and storage of data, ensuring its accuracy and reliability for subsequent analysis. Data analysis: In this step, the rank of departments is calculated based on the obtained scores. Corrective actions: The final step involves implementing corrective actions based on the analysis to ensure continuous improvement and alignment with strategic goals. The current study was carried out in the offices of performance evaluation in planning, human capital development, and the council affairs department at Tehran Municipality in 2025.

MATERIALS AND METHODS

Survey design and data collection

PM is a critical framework that enables organizations to assess their alignment with strategic goals, monitor progress, identify deviations, and address stagnation. A PM system must provide comprehensive insights into the operational dynamics of the organization, facilitating the identification of key areas for improvement. The development of KPIs is central to this process. These indicators should be rooted in various foundational elements, including CSFs, core processes, customer survey results, benchmarking activities, and self-assessment outcomes. By leveraging these diverse data sources, organizations can gain valuable insights into potential bottlenecks and inefficiencies that may impede overall performance. A critical aspect of building an effective PM model is the accurate identification and articulation of core processes. These processes are central to the organization's operations, and their alignment with strategic goals is essential for achieving sustained success. If core processes are inadequately defined or misaligned with the organization's mission, the pursuit of organizational excellence becomes an elusive goal. A robust model ensures that these processes are mapped, managed, and optimized to drive performance at every organizational level. Self-assessment frameworks, such as the EFQM excellence model, are instrumental in guiding organizations through the process of identifying improvement opportunities. These frameworks offer a structured approach to evaluating organizational performance, often highlighting critical areas for development, such as workforce development, training needs,

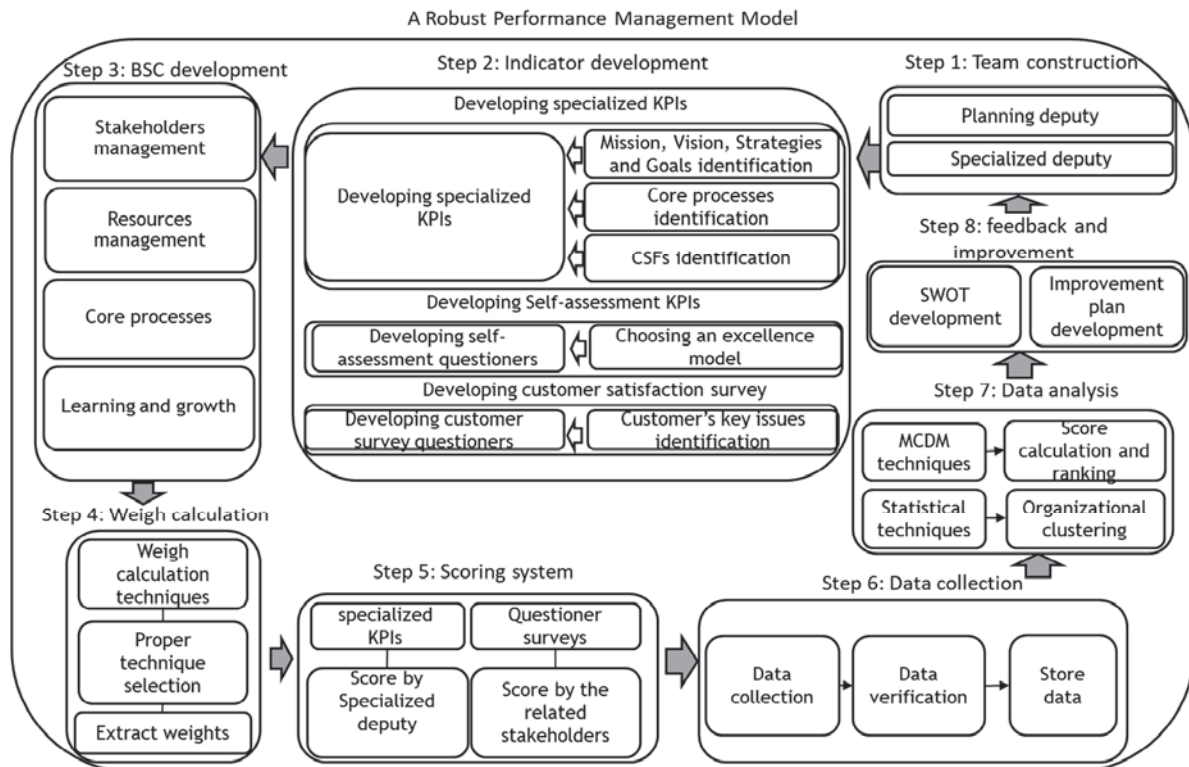


Fig. 1: A robust performance management model

and organizational culture. Addressing these areas is essential for fostering a culture of continuous improvement and aligning employees' capabilities with organizational goals. Additionally, customer surveys are indispensable tools in the pursuit of excellence. Customer feedback provides organizations with invaluable insights into customer expectations, perceptions, and satisfaction levels. This data serves as a foundation for aligning internal processes with customer needs, enabling organizations to adapt their strategies to enhance customer satisfaction and performance continually. The feedback mechanism embedded in this process ensures that organizations remain responsive to evolving market conditions and customer preferences. A truly robust PM model integrates these components—clear identification of core processes, self-assessment tools, customer feedback, and continuous improvement strategies—into a cohesive system that drives organizational performance. The proposed PM model is illustrated in Fig. 1, with its detailed components described as follows.

Step 1: Team formation

The initial phase of any PM project is centered around the formation of a specialized team. The importance of assembling a well-rounded, cross-functional team cannot be overstated, as it serves as the foundation for executing all subsequent stages of the project. The team should consist of PM experts with specialized knowledge in performance measurement and improvement, as well as domain specialists from within the organization who possess deep insights into specific operational areas. This interdisciplinary team is entrusted with the responsibility of developing and executing a PM system that aligns with the organization's strategic goals and objectives.

Step 2: Indicator development

After establishing the PM team, the next crucial phase is the development of performance indicators. A well-structured set of KPIs ensures that organizational objectives are measurable, actionable, and aligned with strategic goals. The systematic

design of indicators allows organizations to track performance, identify inefficiencies, and implement continuous improvements. Performance indicators are broadly categorized into three main groups, each serving a distinct purpose in strategic performance evaluation. Mission-driven indicators are derived from an in-depth analysis of the organization's mission, vision, strategies, and objectives. They ensure alignment between organizational aspirations and measurable outcomes. Key elements include strategic KPIs, goal-specific metrics based on long-term business strategies, and vision-driven benchmarks that reflect future-oriented success measures. CSF-based indicators are developed based on CSFs, which are the key areas that determine organizational success (Rockart, 1979). Developing KPIs based on CSFs effectively ensures that key operational priorities are measured. Process-oriented indicators require a comprehensive understanding of core business processes for effective performance management. By mapping or flowcharting core processes, organizations gain a holistic view of operational activities, facilitating optimization and continuous improvement (Hammer and Champy, 1993). These indicators are designed for functional units and departments with unique objectives. Examples include financial KPIs, operational KPIs, and innovation KPIs. Key analytical questions to refine process indicators include: What are the organization's main products or services? Which key processes support these offerings? Who is responsible for each core process? What are the inputs, outputs, and impacts of these processes? How do these processes align with strategic goals? Additionally, self-assessment KPIs can be developed using established excellence frameworks, such as the EFQM model, which assesses organizational performance based on criteria such as leadership effectiveness, process efficiency, and customer engagement. Customer-centric KPIs should be developed based on key customer concerns and satisfaction drivers. One widely used framework is the Kano Model (Sauerwein et al., 1996), which categorizes customer needs into basic needs (must-have attributes), performance needs (linear satisfaction metrics), and excitement needs (differentiation metrics). By integrating specialized indicators, self-assessment models, and customer survey data, organizations can establish

a comprehensive KPI framework that provides actionable insights for strategic decision-making.

Step 3: BSC development

After identifying and defining KPIs, the next critical phase in the PM model is the development of a BSC. The BSC framework, as introduced by Kaplan and Norton (1992), traditionally consists of four primary perspectives, each of which plays a vital role in strategic performance assessment. However, in this adapted version, the financial perspective is replaced by resource management, and the customer perspective is replaced by stakeholder management. The primary reason for these replacements is to ensure that the developed BSC can be effectively applied to both profitable and non-profit organizations. By focusing on resource management, the framework emphasizes the efficient and sustainable use of resources, which is critical for all types of organizations. Similarly, replacing the customer perspective with stakeholder management broadens the scope to include all relevant stakeholders, making the model more inclusive and adaptable to diverse organizational contexts.

Step 4: Weight calculation

The subsequent phase entails determining the relative weights of the KPIs and aspects of BSC. To achieve this, AHP is employed to derive the weights of the criteria. For this purpose, a hierarchical structure of the indicators is constructed based on the BSC perspectives. Pairwise comparisons are then conducted both between the perspectives and among the indicators within each perspective to compute their respective weights. Consider a pairwise comparison matrix $A = [a_{ij}]$ where i and $j = 1, \dots, n$. Here a_{ij} represents the preference value of the element i over element j . All entries in the matrix are positive $a_{ij} > 0$, and satisfy the reciprocal property, meaning $a_{ji} = \frac{1}{a_{ij}}$. The criteria defined at each level, along with the elements of the subsequent level, are compared pairwise using the 1–9 scale of pairwise comparisons, as illustrated in Table 2. The total number of pairwise comparisons required is given by the formula $\frac{n(n-1)}{2}$.

weight vector $(W_1, \dots, W_n)$ associated with the matrix A can be derived using the normalization of the geometric mean method. Let W_i denote the weight of the element i in matrix A . The geometric mean for

Table 2: The scale of pairwise comparisons

Degree of Importance	Definition	Explanation
1	Equal importance	Two criteria have equal importance according to the objective.
2	Weak or slight	According to the objective, the first criterion has weak or slight importance compared to the second criterion.
3	Moderate importance	The first criterion has moderate importance compared to the second criterion according to the objective.
4	Moderate plus	Between 3 and 5
5	Strong importance	The first criterion has strong importance compared to the second criterion according to the objective.
6	Strong plus	Between 5 and 7
7	Very strong	The first criterion has very strong importance compared to the second criterion according to the objective.
8	Very, very strong	The first criterion is very important to the second criterion according to the objective.
9	Extreme importance	The first criterion has extremely strong importance compared to the second criterion according to the objective.

$$W_i = \frac{\left(\prod_{j=1}^n a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^n \left(\prod_{j=1}^n a_{ij}\right)^{\frac{1}{n}}}, \quad i, j = 1, \dots, n. \quad (1)$$

Each element i is calculated using Eq. 1.

To ensure the reliability and acceptability of the pairwise comparison matrix, a consistency check is performed. This step verifies that the evaluations made during the pairwise comparisons are logically consistent and free from contradictions. Let C be an n -dimensional column vector representing the sum of the weighted values for the importance degrees of the elements in the matrix A . This vector is defined as: $C = [c_i]_{n \times 1} = A \cdot W^T$, $i = 1, \dots, n$. Where W is the weight vector. The Consistency Value (CV) can be expressed as: $CV = [cv_i]_{n \times 1}$ where $cv_i = \frac{c_i}{w_i}$, $i = 1, \dots, n$. Using these values, the inconsistency index can be computed to assess the effectiveness and reliability of the pairwise comparisons. Saaty (1987) introduced the concept of the maximum eigenvalue (γ_{max}) to assess the consistency of pairwise comparison matrices. The maximum eigenvalue is calculated as: $\gamma_{max} = \frac{\sum_{i=1}^n cv_i}{n}$, $i = 1, \dots, n$. Where cv_i represents the consistency value for each element. Using γ_{max} The Consistency Index (CI) is determined as follows: $CI = \frac{\gamma_{max} - n}{n - 1}$. Subsequently, the Consistency Ratio (CR) is defined as: $CR = \frac{CI}{RI}$. Where RI is the Random Index, which depends on the order of the pairwise comparison matrix. Table 3 provides the average values of RI for matrices of different orders. A CR value below 0.1 indicates that the matrix is consistent, the evaluations are rational, and the derived weights are valid. If the CR exceeds

0.10, they should be reviewed and revised to improve consistency.

Step 5: Scoring system

At this stage, KPIs have been developed, and the BSC has been designed. The next crucial step involves collecting data (score) for each KPI, a responsibility assigned to the respective personnel overseeing its execution. Data related to specialized KPIs are gathered from the relevant specialized departments, ensuring accuracy and domain-specific insights. Meanwhile, self-assessment metrics and customer satisfaction data are primarily derived from structured questionnaires. To maintain the reliability and validity of the data, standardized methodologies should be employed in designing these questionnaires, ensuring they effectively capture performance-related insights. Furthermore, the scoring system should be designed to align with organizational strategic objectives, ensuring that KPI measurements reflect actual performance improvements.

Step 6: Data collection

The data collection phase is a critical step in the PM system, as it bridges the design of the scoring system with its practical application. This phase encompasses three primary components: data collection, data verification, and data storage. Data for performance evaluation is gathered from various sources, depending on the nature of the KPIs (Pyzdek and Keller, 2014). Quantitative data, such as financial metrics or operational statistics, are typically obtained from internal systems or automated processes.

Table 3: Consistency ratio

Matrix size	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Qualitative data, such as employee feedback or customer satisfaction surveys, may require tailored collection tools like structured interviews or questionnaires. To ensure comprehensive coverage, it is essential to identify and document the data sources in the earlier stages of the system design (Montgomery, 2017). Once collected, data must be verified to ensure its accuracy, reliability, and relevance. Verification processes may include cross-referencing with existing records, employing statistical methods to identify anomalies, or conducting manual reviews for sensitive qualitative inputs. Ensuring data integrity at this stage minimizes errors that could undermine the credibility of the scoring system and subsequent decision-making processes (Kaplan and Norton ,1992). Proper storage of verified data is critical for long-term analysis and traceability. Data should be stored in centralized databases with secure access controls to prevent unauthorized manipulation or loss (Pyzdek and Keller, 2014).

Step 7: Data analysis

This part used a basic model of DEA to evaluate departments or different organizations with different input structures, operational capacities, and resource availabilities. The mathematical formulation of the model is as follows (Charnes et al., 1978):

$$\text{Max } Z_o = \sum_{r=1}^s u_r y_{ro} \quad (2)$$

s.t

$$\sum_{i=1}^m v_i x_{io} = 1 \quad (3)$$

$$\sum_{r=1}^s u_r y_{rj} - \sum_{i=1}^m v_i x_{ij} \leq 0 \quad (4)$$

$$v_i, u_r \geq 0 \quad (5)$$

where:

Z_o represents the efficiency score of the DMU under evaluation (o).

j, o represent set of DMUs ($j = 1 \dots n, \forall o = 1 \dots n$)

i represent set of inputs ($\forall i = 1 \dots m$)

r represent set of outputs ($\forall r = 1 \dots s$)

x_{ij} and y_{rj} are the inputs and outputs, respectively, for each DMU.

u_r are the weight outputs.

v_i are the weight inputs.

The objective is to find the efficiency score of the target DMU o (Eq. 2). Eq. 3 is the input constraint (efficiency condition). This constraint normalizes the weighted sum of inputs for DMU o to 1, ensuring the efficiency score is bounded between 0 and 1. Eq. 4 ensures that the efficiency score of every DMU (including DMU o) does not exceed 1. Eq. 5 ensures that the weights assigned to peer DMUs are non-negative.

Step 8: Feedback and continuous improvement

A robust feedback mechanism and an effective continuous improvement strategy are crucial for ensuring the sustainability and effectiveness of a PM system. Following the application of quantitative performance analyses, such as DEA, organizations must implement structured feedback loops to enhance decision-making and drive long-term improvements (Montgomery, 2017). Organizational processes can generally be classified into three key categories, each requiring a distinct approach to optimization (Hammer and Champy, 1993). The first category includes processes requiring continuous improvement. These processes exhibit stable performance but benefit from incremental refinements through real-time monitoring and iterative enhancements. Continuous improvement frameworks, such as the PDCA (Plan-Do-Check-Act) cycle (Montgomery, 2017), lean management (Pyzdek and Keller, 2014), and Statistical Process Control (SPC) (Montgomery, 2017), can be utilized to minimize

inefficiencies and enhance operational consistency. The second category pertains to processes in need of re-engineering or redesign. When efficiency and effectiveness fall significantly below expectations, fundamental modifications are required. This approach involves Business Process Reengineering (BPR), a radical redesign of workflows to achieve dramatic improvements in productivity and quality (Hammer and Champy, 1993), as well as process optimization through Machine Learning (ML) and Artificial Intelligence (AI), where predictive analytics can identify bottlenecks and recommend optimized resource allocation (Kaplan and Norton, 1992). The third category involves processes demanding strategic transformation. For processes that no longer align with organizational goals or market dynamics, a comprehensive reassessment of the business model is necessary. This may include strategic foresight and scenario analysis (Kaplan and Norton, 1992), digital transformation to leverage technology for enhanced efficiency, and sustainability integration to align with environmental and social governance principles (Pyzdek and Keller, 2014). A structured approach for evaluating organizational feedback and identifying areas for improvement is SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats). It provides a strategic framework for categorizing internal and external factors affecting performance (Kaplan and Norton, 1992). By leveraging SWOT analysis, organizations can develop targeted improvement strategies that align internal capabilities with external opportunities while mitigating risks. To ensure that feedback leads to measurable improvements, organizations should implement structured feedback mechanisms, such as KPI monitoring dashboards, which allow for real-time tracking of performance data using business intelligence tools (Kaplan and Norton, 1992), employee and customer feedback systems through surveys, focus groups, and sentiment analysis to gather qualitative insights (Pyzdek and Keller, 2014), and benchmarking against industry best practices, comparing performance metrics with industry leaders to identify gaps and areas for improvement (Hammer and Champy, 1993). For well-performing processes, promotional and marketing strategies can amplify their impact, ensuring they remain competitive. For underperforming processes, targeted interventions should include forecasting models, which use historical data and

predictive analytics to anticipate future performance trends (Montgomery, 2017), targeted training and competency development to ensure employees possess the necessary skills to optimize performance (Pyzdek and Keller, 2014), financial resource allocation adjustments through data-driven budgeting to improve operational efficiency, and continuous improvement initiatives (such as Kaizen and Six Sigma) to implement structured methodologies that reduce waste and variation (Pyzdek and Keller, 2014). Benchmarking against top-performing organizations also allows for the adoption of best practices (Hammer and Champy, 1993). Recent advancements in AI and ML have revolutionized the way organizations analyze feedback and implement continuous improvement. AI-driven systems can detect inefficiencies in real-time using anomaly detection algorithms, automate decision-making processes for enhanced agility, and optimize predictive models to anticipate future challenges and recommend proactive solutions (Kaplan and Norton, 1992).

RESULTS AND DISCUSSION

Urban governance is a complex and dynamic process that requires systematic performance management to ensure efficiency, effectiveness, and citizen satisfaction. This study examines a hypothetical municipality, referred to as Metropolitan City X, which comprises four municipal organizations responsible for delivering a range of public services. These organizations include: Urban Planning and Development Authority (UPDA): Focused on urban development and infrastructure planning. Public Transportation and Mobility Department (PTMD): Responsible for managing public transportation systems and mobility solutions. Environmental and Waste Management Authority (EWMA): Tasked with environmental protection and waste management services. Digital Transformation and Smart Governance Unit (DTSGU): Dedicated to implementing digital innovations and smart governance initiatives. These organizations collectively serve the 22 distinct districts of Metropolitan City X, each with unique needs and challenges. By analyzing their performance, this study aims to provide insights into improving urban governance and enhancing service delivery across the city. According to the proposed model, an expert team is formed, consisting of PM experts with specialized knowledge in performance

Table 4: BSC of the organizations

DMUs	Learning and growth	Internal processes	Stakeholder management	Resource management
UPDA	Training hours per employee Employee satisfaction and retention rate	Project completion rate (%)	Public satisfaction with urban planning (%)	Budget adherence for urban development projects (%)
	Innovation rate in urban planning projects	Compliance with zoning regulations (%)	Customer feedback on housing projects (%)	Cost efficiency in infrastructure projects
		Sustainability of infrastructure development (%)	Community engagement rate	Return on investment (ROI) for urban development projects
PTMD	Employee training and development hours per employee	Service frequency and coverage (trips per day, area served)	Customer satisfaction with public transportation (%)	Cost per passenger mile
	Innovation in mobility services (% of new technology adoption)	Fleet maintenance and downtime rate (%)	On-time performance rate (%)	Revenue generation from public transport (%)
	Employee satisfaction and retention rate (%)	Integration of sustainable transport solutions (%)	Passenger complaints and resolution rate (%)	Cost savings from energy-efficient transportation
EWMA	Employee training and development hours per employee	Waste diversion rate (%)	Public satisfaction with waste management services (%)	Cost per ton of waste processed
	Innovation in waste management technologies (%)	Compliance with environmental regulations (%)	Compliance with waste segregation policies (%)	Revenue from recycling programs (%)
	Employee engagement and retention rate (%)	Operational efficiency in waste collection and disposal (tons per truck per day)	Response time to environmental complaints (hours)	Operational cost reduction in waste management (%)
DTSGU	Employee training hours in digital skills per employee	Digital service delivery speed (average response time, hours)	Citizen satisfaction with digital government services (%)	Cost per digital project implemented
	Innovation rate in digital governance (number of new technologies implemented)	System uptime and reliability (%)	Adoption rate of digital services by citizens (%)	Return on investment (ROI) from smart governance initiatives (%)
	Employee engagement and retention rate (%)	Digital solution integration rate (%)	Public trust in smart governance systems (%)	Operational cost reduction from digitalization (%)

measurement and improvement, as well as domain specialists from each organization. Indicators are developed, BSCs are constructed, and the weights of the indicators are calculated using the AHP method. Table 4 presents the BSCs.

The EFQM model, a non-prescriptive and widely recognized framework, is selected as an excellent tool for self-assessment. This model is structured around three core categories: Direction, Execution, and Results, each of which is further divided into specific

subcriteria. These categories and their corresponding subcriteria are as follows: Direction: Purpose, vision, and strategy: Defining the organization's mission, long-term vision, and strategic objectives. Organizational culture and leadership: Fostering a culture of excellence and ensuring effective leadership. engaging stakeholders: Building strong relationships with stakeholders to align interests and expectations. Execution: Creating sustainable value: delivering value to stakeholders in a sustainable

Table 5: EFQM Subcriteria in BSC

Learning and growth	Internal processes	Stakeholder management	Resource management
Purpose, vision, and strategy	Driving performance and transformation	Engaging stakeholders	Managing resources and the ecosystem
Organizational culture and leadership		Customer results	Business results
Creating sustainable value		People results Society results	

Table 6: Score of the organizations in each aspect of the BSC

DMUs	Learning and growth	Internal processes	Stakeholder management	Resource management
DTSU	60.80%	70.00%	30.00%	10.00%
PTMD	42.53%	37.94%	18.71%	65.09%
EWMA	38.62%	77.81%	38.51%	67.93%
UPDA	35.41%	52.12%	33.17%	55.30%

manner. driving performance and transformation: Implementing initiatives to enhance performance and drive organizational change. Managing resources and ecosystem: Optimizing the use of resources and managing the broader ecosystem effectively. results: Customer results: Measuring outcomes related to customer satisfaction and service delivery. People results: Evaluating employee engagement, development, and well-being. Society results: Assessing the organization's impact on society and the environment. Business results: Analyzing financial and operational performance. Table 5 is provided to illustrate how these subcriteria of the EFQM model align with the most relevant aspects of the BSC. This alignment ensures a comprehensive evaluation framework that integrates the strengths of both models, enabling organizations to assess their performance holistically and identify areas for improvement.

Additionally, customer survey questions have been incorporated into the stakeholder management aspect of the BSC. This integration ensures that the perspectives and feedback of stakeholders, particularly customers, are systematically captured and analyzed as part of the performance evaluation process. By aligning the organization's BSC with specialized KPIs and including stakeholder input through customer surveys, the framework provides a comprehensive and balanced view of performance. This approach not only measures internal efficiency and effectiveness but also reflects external stakeholder satisfaction, enabling a more holistic assessment

of organizational success. The AHP is employed to determine the weights of KPIs within each aspect of the BSC for every organization. This method ensures a systematic and objective approach to prioritizing KPIs based on their relative importance. The data for the KPIs are collected, verified, and aggregated according to Table 6, ensuring accuracy and consistency in the evaluation process. By applying AHP, the weights assigned to each KPI reflect their significance in achieving the strategic objectives of the organization.

In this step, DEA is utilized to calculate the efficiency of the organizations. The DEA model is structured by considering the learning and growth, and internal processes aspects as inputs, while stakeholder management and resource management are treated as outputs. This configuration allows for a comprehensive evaluation of how effectively organizations convert their internal capabilities and processes into tangible outcomes related to stakeholder satisfaction and resource utilization. The results of the DEA analysis are presented in Table 7, which provides a clear overview of the efficiency scores for each organization. These scores highlight the relative performance of the organizations in leveraging their inputs to achieve desired outputs. By identifying efficient and inefficient units, the DEA results offer valuable insights into areas where improvements can be made to enhance overall performance. This step is crucial for understanding the operational effectiveness of the organizations and guiding strategic decision-making.

According to the obtained results, both the

Table 7: Efficiency of the organizations

DMUs	Efficiency
DTSGU	67.35%
PTMD	46.03%
EWMA	100.00%
UPDA	100.00%

Table 8: Score of the districts in each aspect of the BSC

DMUs	Learning and growth	Internal processes	Stakeholder management	Resource management
1	61%	70%	30%	10%
2	43%	38%	19%	65%
3	39%	78%	39%	68%
4	35%	52%	33%	55%
5	55%	55%	6%	40%
6	68%	26%	97%	1%
7	63%	52%	65%	88%
8	89%	22%	17%	73%
9	57%	57%	10%	44%
10	44%	26%	72%	39%
11	14%	51%	84%	58%
12	42%	17%	8%	43%
13	4%	90%	98%	95%
14	41%	30%	53%	93%
15	77%	18%	47%	28%
16	24%	21%	55%	51%
17	13%	28%	95%	6%
18	88%	66%	19%	20%
19	59%	96%	85%	3%
20	52%	81%	69%	61%
21	49%	31%	99%	38%
22	9%	11%	15%	93%

EWMA and the UPDA achieved the same efficiency score and were ranked first. The DTSGU secured the second rank, while the PTMD was ranked third. This scenario highlights a limitation of the DEA model, as it often fails to differentiate between units that achieve the same efficiency score, leading to tied rankings. This issue can become more pronounced as the number of DMUs increases, making it difficult to provide a clear and actionable ranking. For further investigation, consider a scenario where 22 DMUs (districts) are evaluated using the DEA model. Table 8 provided scores of the districts in each aspect of the BSC, and Table 9 provided the efficiency of the organizations.

According to Table 9, DMUs 6, 13, 17, and 22 have all achieved 100% efficiency and are tied for the first rank based on the DEA results. While the DEA model effectively identifies efficient and inefficient DMUs, it faces a significant limitation: it cannot provide a

detailed ranking when multiple units achieve the same efficiency score. This issue becomes particularly problematic as the number of DMUs increases, leading to tied rankings and reduced clarity in performance evaluation. This limitation highlights the necessity of integrating complementary methods, such as TOPSIS, to refine the evaluation process. This method offers granular insights into the relative performance of each DMU by considering multiple criteria and assigning distinct scores and rankings. By combining the strengths of the DEA model with TOPSIS, organizations can overcome the shortcomings of the DEA model and achieve a more comprehensive and differentiated assessment. This integrated approach enables better-informed decision-making, ensuring that resources are allocated effectively and performance improvements are targeted where they are needed most. In this part, the TOPSIS method is employed to rank the organizations, ensuring that

Table 9: Efficiency of the districts

DMUs	Efficiency	Rank
1	13%	14
2	27%	11
3	25%	13
4	26%	12
5	9%	17
6	100%	1
7	48%	8
8	47%	8
9	11%	15
10	86%	4
11	84%	5
12	32%	9
13	100%	1
14	72%	7
15	80%	6
16	93%	3
17	100%	1
18	10%	16
19	26%	12
20	30%	10
21	97%	2
22	100%	1

Table 10: Weights of the aspects of the BSC

Aspects	Learning and Growth	Internal processes	Stakeholder management	Resource management
Weights	15.00%	25.00%	35.00%	25.00%

each organization is assigned a distinct and specific rank. To accomplish this, the AHP technique is utilized to determine the weights of the criteria, as illustrated in Table 10. This approach ensures a systematic and objective ranking process based on the calculated weights and performance metrics.

The TOPSIS method (Hwang and Yoon, 1981) operates by calculating the geometric distance of each alternative from both the positive ideal solution (PIS) and the negative ideal solution (NIS). The optimal alternative is selected based on two key criteria: it should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. This dual-criterion approach ensures that the chosen alternative is the most favorable, balancing proximity to the best possible outcomes and distance from the worst possible outcomes. The constructed BSC serves as the decision matrix, denoted as $(D = [k_{ij}]_{mn})$ where the rows ($i = 1, \dots, m$) show alternatives (organizations) and columns ($j = 1, \dots, n$) show criteria

(aspects). Each element x_{ij} in the matrix indicates the score of the i -th alternative with respect to the j -th criterion. To normalize the decision matrix, the vector normalization method is applied, as described by Eq. 6:

$$R_{ij} = \frac{k_{ij}}{\sqrt{\sum_{i=1}^m k_{ij}^2}}, \text{ for all } i = 1, \dots, m, \quad j = 1, \dots, n. \quad (6)$$

In this equation, R_{ij} represents the normalized value of x_{ij} . This normalization process ensures that the criteria are scaled uniformly, allowing for a fair and consistent comparison across different alternatives. Now, by multiplying each normalized value R_{ij} by its corresponding weight W_j , the weighted normalized matrix is constructed by Eq. 7:

$$V_{ij} = W_j R_{ij}. \quad (7)$$

Then, the positive ideal solution, the maximum value of alternatives in each attribute, $(V^+ = V_1^+, V_2^+, \dots, V_n^+)$ and the negative ideal solution, minimum value of alternatives in each attribute $(V^- = V_1^-, V_2^-, \dots, V_n^-)$ can be constructed. So, the separation measure can be calculated by Eq. 8 and by Eq. 9

$$S_i^+ = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^+)^2}, \text{ for all } i = 1, \dots, n. \quad (8)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^-)^2}, \text{ for all } i = 1, \dots, n. \quad (9)$$

Now we can calculate the relative closeness to the ideal solution by Eq. 10

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}, \text{ for all } i = 1, \dots, n. \quad (10)$$

So, the final ranking is achieved, and we can use the ranking for future actions.

Table 11 and Table 12 present the final scores derived from the TOPSIS method. According to the results, EWMA achieves the top rank with a score of 94.67%, while UPDA secures the second rank with a score of 46.86%. Interestingly, the DEA method assigns 100% efficiency to both organizations, indicating that DEA is unable to differentiate between their performance levels.

According to the tables, DEA assigned 100% efficiency to the 6th and 17th DMUs, while TOPSIS ranked them 20th and 21st, respectively. The primary reason for this significant discrepancy lies

Table 11: TOPSIS score of the organizations

DMUs	Score
EWMA	94.67%
UPDA	46.86%
PTMD	39.17%
DTSGU	38.13%

Table 12: TOPSIS score of the districts

DMUs	Score	Rank
1	87%	10
2	86%	13
3	89%	5
4	87%	8
5	86%	14
6	82%	20
7	89%	4
8	87%	12
9	87%	11
10	85%	18
11	87%	6
12	85%	15
13	94%	1
14	87%	7
15	85%	17
16	85%	16
17	82%	21
18	87%	9
19	90%	3
20	90%	2
21	83%	19
22	34%	22

in the fundamental differences between the two methodologies. DEA evaluates efficiency based on the ratio of outputs to inputs, meaning that DMUs 6 and 17 achieved high efficiency due to their excellent performance in stakeholder management, despite poor performance in resource management. However, TOPSIS takes a more comprehensive approach by considering multiple criteria and does not overlook such imbalances, providing a more detailed and nuanced evaluation of each DMU. Similarly, DMU 22 was rated 100% efficient by the DEA but received only a 34% score and a 22nd rank by TOPSIS. This inconsistency arises because DEA incorporates the scores of learning and growth, as well as internal processes, into the input section, which allowed DMU 22 to achieve full marks despite its poor performance in other aspects. In contrast, TOPSIS evaluates each DMU by comparing its performance across all criteria to the best-performing DMU, thereby addressing such conflicts and offering a more balanced assessment. On the other hand, DMU 13 was rated 100% efficient by the DEA and also secured the first rank with a 94% score in TOPSIS, indicating strong overall performance. The remaining conflicts between DEA and TOPSIS rankings can be attributed to the same underlying reasons: DEA's focus on input-output ratios often overlooks imbalances in specific criteria, while TOPSIS provides a more holistic and detailed comparison across all aspects. This demonstrates that TOPSIS offers a more informative and reliable ranking system, particularly when evaluating DMUs with varying strengths and weaknesses across multiple dimensions.

CONCLUSION

This study introduced an eight-step conceptual performance management model that addressed the limitations of existing frameworks by offering a comprehensive, visually intuitive, and step-by-step approach. The model began with forming a team of performance management experts and domain specialists, followed by integrating the organization's mission, vision, strategies, processes, and stakeholder perspectives into a structured system of KPIs. These KPIs were categorized into specialized KPIs (derived from core processes and strategic factors), self-assessment KPIs (based on excellence models), and customer survey KPIs (capturing external feedback). The KPIs were mapped into the BSC framework,

with weights determined using the AHP. Scores were assigned to KPIs, and data were collected, cleaned, and stored for analysis. Mathematical tools like DEA and TOPSIS were used to calculate efficiency and rank organizations, followed by implementing corrective actions for continuous improvement. A case study of a hypothetical municipality demonstrated the model's applicability, revealing discrepancies between DEA and TOPSIS results, which were analyzed to highlight its ability to deliver nuanced and actionable outcomes. By combining data-driven decision-making with a holistic evaluation framework, this model enabled organizations to achieve continuous improvement and strategic alignment, making it a valuable tool for enhancing performance across diverse contexts.

AUTHOR CONTRIBUTIONS

K. Fahimi performed the literature review, conducted the conceptual model and numerical results, compiled the data, analyzed and interpreted the data, and prepared the manuscript text and edition. A. Alaeddini, M. Poramezan, and F. Kabuli performed the literature review and applied the model and designed the BSC.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the authors have witnessed ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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ABBREVIATIONS

<i>PM</i>	Performance Management	<i>EFQM model</i>	European Foundation for Quality Management model
<i>MBO</i>	Management by Objectives	<i>SCOR model</i>	Supply Chain Operations Reference Model
<i>KPIs</i>	Key Performance Indicators	<i>SCC</i>	Supply Chain Council
<i>BSC</i>	Balanced Scorecard	<i>MCDM</i>	Multi-Criteria Decision-Making
<i>KRIs</i>	Key Result Indicators	<i>TOPSIS</i>	Technique for Order of Preference by Similarity to Ideal Solution
<i>RI</i>	Result Indicators	<i>AHP</i>	Analytical Hierarchical Process
<i>PIs</i>	Performance Indicators	<i>ANP</i>	Analytic Network Process
<i>JUSE</i>	Union of Japanese Scientists and Engineers	<i>VIKOR</i>	Vise Kriterijumska Optimizacija I Kompromisno Resenje
<i>TQM</i>	Total Quality Management	<i>PROMETHEE</i>	Preference Ranking Organization METHod for Enrichment Evaluation
<i>MBNQA</i>	Malcolm Baldrige National Quality Award	<i>DEA</i>	Data Envelopment Analysis
		<i>DMUs</i>	Decision-Making Units
		<i>CSFs</i>	Critical Success Factors
		<i>CI</i>	Consistency Index
		<i>CR</i>	Consistency Ratio
		<i>RI</i>	Random Index
		$A = [a_{ij}]$	Pairwise comparison matrix.
		a_{ij}	Amount of preference of element i to element j .

W_i	Weight of element i	<i>SWOT</i>	Strengths, Weaknesses, Opportunities, and Threats
$(W_1, \dots, W_n)$	Vector of weights.	<i>UPDA</i>	Urban Planning and Development Authority
C	An n-dimensional column vector.	<i>PTMD</i>	Public Transportation and Mobility Department
$CV = [cv_i]_{1 \times n}$	Consistency value.	<i>EWMA</i>	Environmental and Waste Management Authority
$\gamma_{\max}$	Maximum eigenvalue.	<i>DTSGU</i>	Digital Transformation and Smart Governance Unit
CI	Consistency index.	<i>PIS</i>	Positive ideal solution
RI	Average random index.	<i>NIS</i>	Negative ideal solution
Z_o	Efficiency score of the DMU	$D = [k_{ij}]_{mn}$	Decision matrix.
j, o	Set of DMUs		
i	Set of inputs		
r	Set of outputs		
x_{ij}	Amount of input i for DMU j	k_{ij}	A score of alternatives i in criteria j .
y_{rj}	Amount of output r for DMU j	R_{ij}	Normalized amount of x_{ij} .
u_r	Weight output r	V_{ij}	Weighted normalized amount of x_{ij} .
v_i	Weight input i	$(V^+ = V_1^+, V_2^+, \dots, V_n^+)$	The maximum value of alternatives in each attribute.
<i>PDCA cycle</i>	Plan-Do-Check-Act cycle	$(V^- = V_1^-, V_2^-, \dots, V_n^-)$	The minimum value of alternatives in each attribute.
<i>SPC</i>	Statistical Process Control		
<i>BPR</i>	Business Process Reengineering		
<i>ML</i>	Machine Learning	S_i^+	Positive separation measure.
<i>AI</i>	Artificial Intelligence	S_i^-	Negative separation measure.

C_i^+

Relative closeness to the ideal solution.

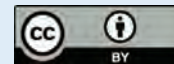
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ORIGINAL RESEARCH PAPER

A comparative examination of perceptions of artificial intelligence's role in small businesses

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ABSTRACT

BACKGROUND AND OBJECTIVES: As artificial intelligence increasingly transforms business potential, its adoption in small businesses has become a growing interest. This study explores college students' perceptions of artificial intelligence in the context of small businesses, comparing insights from Kuwait and Malaysia. With small businesses playing a pivotal role in the economic growth of both countries, understanding how future employees perceive artificial intelligence can provide valuable guidance for educators, entrepreneurs, and policymakers. The research aims to investigate key factors such as artificial intelligence awareness, perceived benefits and challenges, willingness to adopt artificial intelligence technologies, and the perceived effectiveness of artificial intelligence in improving business operations. In addition, a bibliometric analysis was conducted to compare the research trends and national emphasis on artificial intelligence in business within the two countries.

METHODS: A quantitative research approach was employed using a structured survey distributed to a total of 834 university students from Kuwait and Malaysia. The survey collected data on various dimensions, including artificial intelligence awareness, perceived utility, anticipated challenges, and readiness to engage with artificial intelligence in small business settings. The data were statistically analyzed to determine significant differences and similarities across the two national contexts. Also, a bibliometric analysis was carried out to explore the scholarly output and collaboration trends related to artificial intelligence and business in both countries.

FINDINGS: Statistical analysis of the survey data from 834 students (433 from Malaysia and 401 from Kuwait) revealed high mean scores across all constructs, ranging from 3.90 to 4.08 on a 5-point Likert scale, indicating overall positive perceptions of AI's role in small businesses. Independent-samples t-tests showed no significant differences ($p > 0.05$) between the two countries regarding AI awareness, perceived benefits, anticipated challenges, willingness to adopt AI, and perceived impact on SMEs. Reliability coefficients (Cronbach's α) for the constructs ranged from 0.73 to 0.86, confirming internal consistency. Additionally, bibliometric analysis showed that Malaysia produced 105 relevant publications from 2010–2024, with 1,872 total citations, while Kuwait produced 10 publications from 2018–2024, with 234 citations. Despite fewer publications, Kuwait demonstrated higher average citations per paper (23.4 vs. 17.83), indicating a high-impact research contribution.

CONCLUSION: This study underscores the universal recognition of artificial intelligence's value in small businesses among young professionals in Kuwait and Malaysia. The findings highlight the need for context-sensitive policies, focused artificial intelligence education, and hands-on support mechanisms for small enterprises. Cross-cultural collaboration and targeted research initiatives are recommended to responsibly harness artificial intelligence's potential and drive sustainable innovation in the small business sector.

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INTRODUCTION

Small and Medium-Sized Enterprises (SMEs) play a crucial role in the global economy, contributing to innovation, employment, and economic growth. The significant technical advancements over the past two decades have contributed to the reallocation of resources. Internet resources and the current accessibility of big data and Artificial Intelligence (AI) have profoundly transformed the corporate environment. These developments have been beneficial in that production has been more efficient and faster, while communication has become instantaneous. AI refers to the development of computer systems that can perform tasks that typically require human intelligence, such as speech recognition, decision-making, problem-solving (Petricini *et al.*, 2023), and self-learning (Soni *et al.*, 2020; Al-Hunaiyyan *et al.*, 2021C). AI plays a significant role in transforming small businesses across various aspects, offering opportunities for efficiency, growth, and innovation (Boucher *et al.*, 2022). In addition, AI empowers small businesses by providing tools and capabilities and contributes to the sustainable growth of an increasingly digital and competitive business (Petricini *et al.*, 2023). Furthermore, small businesses can leverage automation and AI to streamline routine tasks and make informed decisions based on customer data (Munyengeterwa *et al.*, 2023; Bhattacharya, 2020), and can transform industries by increasing efficiency, reducing costs, improving product quality, and enhancing customer service (Kumar and Kalse, 2021). Moreover, AI can extract valuable insights from vast amounts of data, leading to more informed decision-making and better business outcomes (Campbell *et al.*, 2020), improved marketing strategies (Francis *et al.*, 2023). However, previous studies have indicated that challenges such as a lack of technical skills, high implementation costs, and resistance to change are common obstacles faced by SMEs (Chalmers *et al.*, 2020). In addition, the adoption of AI among small businesses has been limited due to various barriers, including a lack of knowledge, privacy concerns, bias, and resources (Sharma, 2023; Boucher *et al.*, 2022). Despite the growing relevance of AI in developing economies such as Kuwait, where SMEs are critical to economic growth and job creation, there remains a limited understanding of how future business leaders perceive AI, especially in terms of its practical applications, benefits, and

challenges. Malaysia's national strategy strongly supports entrepreneurs and small business owners through policies and initiatives that foster digital transformation and technology adoption (Malaysian Investment Development Authority (MIDA), 2021; Ministry of International Trade and Industry (MITI), 2018). Central to this strategy is the Malaysia Digital Economy Blueprint (MyDIGITAL), which aims to advance the country's digital economy by promoting the integration of AI and other digital tools among SMEs (Malaysia Digital Economy Corporation (MDEC), 2020). The government provides financial incentives, such as the SME Digitalisation Grant Scheme and Industry4WRD Intervention Fund, which help SMEs adopt digital technologies and enhance operational efficiency (Malaysia Digital Economy Corporation (MDEC), 2020). Additionally, agencies like Malaysia Digital Economy Corporation (MDEC) actively facilitate training and capacity-building programs, equipping entrepreneurs with the necessary skills to leverage AI and other digital solutions effectively. Similarly, Kuwait's national strategy supports entrepreneurs and small business owners by focusing on economic diversification and fostering a knowledge-based economy through digital innovation and entrepreneurship. The Kuwait Vision 2035 initiative (New Kuwait, 2018), known as "New Kuwait," aims to reduce dependency on oil revenue and stimulate the growth of the private sector, particularly by empowering SMEs. The National Fund for SME Development (2021) is a key component, providing financial support, training, and resources to nurture entrepreneurial ventures and enable small business growth. In addition, programs led by the Kuwait Foundation for the Advancement of Sciences (KFAS, 2020) promote digital skills and AI literacy, preparing entrepreneurs to integrate AI and digital tools into their businesses. Encouraging individuals to engage in entrepreneurship is crucial for the vision and mission of countries, particularly in the context of the knowledge economy, which aligns with the vision and mission of the State of Kuwait. The "New Kuwait" development plan, outlined by five strategic directions and seven pillars, aims to position Kuwait as a leading regional hub in finance, culture, and institutions by 2035. This plan emphasizes modern education as a key focus area (Al-Hunaiyyan and Al-Sharhan, 2009), developing a diverse and prosperous economy to reduce the country's dependence on

income from oil exports (Alkharafi *et al.*, 2024). Despite the rapid advancement of AI and its growing relevance in small business transformation, the rate of AI adoption among SMEs remains relatively low, particularly in developing economies. For example, a global survey by IBM in 2023 found that only 35% of small businesses have actively adopted AI technologies, citing challenges such as cost, skills shortage, and lack of awareness. In Kuwait, where SMEs contribute approximately 40% to non-oil GDP (KFAS, 2020), the National Fund for SME Development reported that less than 10% of funded businesses use AI solutions (National Fund for SME Development, 2021). Similarly, in Malaysia, although government support is extensive, a 2022 SME Corp report showed that only 21.8% of SMEs have adopted any form of AI (SME Corporation Malaysia, 2022). This gap between technological potential and practical adoption, combined with limited insights into how future business professionals perceive AI, highlights a significant problem. Understanding these perceptions is essential for designing effective AI education and policy interventions. Despite the increasing global attention on AI, its actual adoption among SMEs remains limited—especially in developing nations. According to IBM's 2023 Global AI Adoption Index, only 35% of small businesses worldwide have actively adopted AI technologies, citing barriers such as cost, lack of technical skills, and awareness. In Kuwait, SMEs contribute around 40% to the non-oil GDP (KFAS, 2020), yet the National Fund for SME Development notes that fewer than 10% of supported businesses utilize AI-based tools. Similarly, in Malaysia, while government efforts are extensive, only 21.8% of SMEs had adopted any form of AI by 2022 (SME Corp Malaysia). This gap between AI's transformative potential and its underutilization, particularly by future business leaders, highlights a critical knowledge and readiness gap that this study seeks to address.

Research aim, objectives, and hypothesis

This study seeks to gather quantitative data from business college students in Malaysia and Kuwait to assess their views on these benefits, thereby providing a clearer picture of how future business leaders perceive the value of AI in enhancing competitive advantage within small businesses. Examining these challenges through the lens of student awareness

and perceptions will elucidate the gaps in knowledge and support that may hinder successful AI adoption. Another objective is to explore the comparative insights into the benefits of AI adoption as understood by students from both countries (Chatterjee and Kar, 2020). Realizing these benefits requires future business leaders who understand AI's capabilities and limitations and help educators to better prepare students and equip them with the skills needed for technology-driven business environments. The study seeks to highlight students' readiness and willingness to adopt AI, offering critical insights for educators and policymakers to align academic programs with the digital competencies necessary for a modern workforce. By capturing comparative insights, this research provides an understanding of how cultural and economic contexts shape student perceptions of AI. Through a comparative examination of Kuwaiti and Malaysian students, the study illuminates regional differences and similarities in perceptions of AI, contributing to global insights on AI education trends. The specific objectives are:

1. *Investigate students' awareness and understanding of AI technologies as relevant to small businesses in Kuwait and Malaysia.*
2. *Identify and compare students' perceptions of the benefits of AI across the two countries.*
3. *Examine the challenges students anticipate regarding AI implementation within small businesses.*
4. *To compare the thematic focus, research productivity, and impact of AI and business research between Kuwait and Malaysia.*

Given that Malaysia has developed an advanced digital infrastructure through its national digital transformation plan, supported by comprehensive government initiatives and substantial research investments, this study hypothesizes that Malaysian students are likely to perceive AI in SMEs more positively than Kuwaiti students. Furthermore, this hypothesis is reinforced by a bibliometric analysis within the study, which indicates a higher volume of AI-related research and initiatives in Malaysia. Consequently, the hypothesis guiding this study is as follows:

Hypothesis: There is a significant difference in AI perceptions between Malaysian and Kuwaiti students, with Malaysian students demonstrating a stronger understanding and acceptance of AI's potential in SMEs.

Literature review

This literature review explores key themes in AI awareness and its integration within SMEs and compares insights from previous studies on perceptions of AI's benefits, challenges, and knowledge levels among young adults, particularly students, in different cultural contexts.

Awareness of AI

Awareness of AI technologies in education plays a crucial role in shaping the perceptions and readiness of students for future employment in a landscape increasingly influenced by AI (Boucher *et al.*, 2022; Chalmers *et al.*, 2020). Research indicates that understanding AI's functionalities and potential benefits can enhance students' learning experiences and prepare them for a workforce that increasingly demands proficiency in AI-related skills (Alsharif *et al.*, 2021; Hussain *et al.*, 2022). According to Enholm *et al.*, (2021), AI is a wide-ranging set of technologies that promise several advantages for organizations in terms of added business value. A frequently cited definition of AI literacy was developed by Long *et al.*, (2021), who define it as a set of competencies that enables individuals to critically evaluate AI technologies, communicate and collaborate effectively, and use AI as a tool online, at home, and in the workplace. Awareness and understanding of AI technology are critical for successful adoption in business environments. Studies have shown that students, particularly those pursuing business and technology degrees, tend to have a basic understanding of AI, though their depth of knowledge is often limited (Zawacki-Richter *et al.*, 2019). According to (Senadjki *et al.*, 2023; Singh and Kumar, 2022), awareness, empowerment, and implementation of AI positively impact business competitiveness, with innovations in technology, society, and environment playing a mediating role. Similarly, Studies have shown that awareness of AI technologies influences perceptions of potential benefits and challenges associated with AI adoption in SMEs (Enholt *et al.*, 2021). (Zawacki-Richter *et al.*, 2019) found that while students recognize AI concepts, many lack an in-depth understanding of its applications and underlying mechanisms. This superficial understanding is a barrier to AI adoption in small businesses, as future leaders must possess both a general knowledge of AI's capabilities and a

practical understanding of its implementation in resource-constrained environments (Holmes *et al.*, 2022). Awareness of AI among small business owners is often limited, with many lacking a comprehensive understanding of AI's potential and its practical applications. Studies indicate that, while some SMEs recognize AI's capacity for improving efficiency and competitiveness, awareness is often surface-level and concentrated on well-known applications, such as customer service chatbots or recommendation algorithms (Zawacki-Richter *et al.*, 2019). According to Kumar and Kalse (2021), small business owners may be aware of AI's broad implications but lack knowledge of specific tools and applications that can benefit their operations directly. This knowledge gap is attributed to various factors, including limited resources, restricted access to training, and minimal exposure to AI-driven technologies (Sivarajah *et al.*, 2023). (Kadhim, 2024) indicated that the growing awareness and impact of AI in various sectors, particularly education, healthcare, and Business, and pointed out that AI technologies contribute to spreading awareness and educating users through the availability of programs that detect and combat fake news (Kadhim, 2024).

Perceived benefits of AI in small businesses

Perceptions of AI's role in small businesses have garnered considerable attention in recent years, particularly as educational institutions strive to equip students with relevant knowledge in technology and business (Zawacki-Richter *et al.*, 2019; Crockett *et al.*, 2023). The adoption of AI technologies holds the potential to significantly impact small businesses, enhancing their competitiveness and operational efficiency (Boucher *et al.*, 2022). The literature emphasizes the diverse nature of small enterprises, encompassing a wide range of industries, sizes, and operational models. In addition, research highlights numerous potential benefits of AI adoption for small businesses (Haenlein and Kaplan, 2019). These include improved decision-making, increased efficiency, enhanced customer experience, cost savings, and the ability to leverage data for strategic insights (Wallace, 2023). AI technologies offer small businesses innovative solutions to address operational challenges (Petricini *et al.*, 2023), possess the capacity to significantly enhance small business efficiency through the automation of jobs and the optimization

of operations (Crockett *et al.*, 2023). According to Kumar and Kalse (2021), AI utilizes machine learning algorithms to analyze data and produce valuable insights that can inform decision-making processes. This can also enhance operational efficiency and ultimately boost productivity (Wamba-Taguimdje *et al.*, 2020; Pfau and Rimpp, 2020), offering round-the-clock assistance, addressing common inquiries, and promptly handling problems in real-time (Chalmers *et al.*, 2020). In addition, AI can enhance operational efficiency, boost decision-making capabilities, support customer service, and eventually augment production (Pfau and Rimpp, 2020). Furthermore, utilizing AI-powered chatbots or virtual assistants enables small enterprises to receive assistance in customer service and support (Hale, 2018). AI can enable small businesses to optimize their marketing and advertising strategies, target the right audience with personalized messages, and ultimately drive more sales (Huang and Rust, 2020). In addition, AI can also automate various marketing tasks, such as email marketing, social media management, and content creation (Huang and Rust, 2020). The use of AI in marketing can also enhance customer personalization and engagement, analyzing customer data and preferences, and can help small businesses deliver personalized marketing (Lee *et al.*, 2019). Furthermore, the utilization of Natural Language Processing (NLP), a branch of AI, allows machines to comprehend and analyze human language, leading to a substantial optimization of diverse business operations (Alzayed and Al-Hunaiyyan, 2021). Concerning human resources, the adoption of AI can lead to the development of employment policies that are more strategic, fair, and effective. This can improve employee satisfaction, productivity, and retention (Alainati *et al.*, 2023B), ultimately contributing to the overall success and growth of the business (Lee *et al.*, 2023; Ying *et al.*, 2023). In addition, the potential for AI to contribute to self-learning and innovation within SMEs is another frequently cited benefit. AI-powered tools that facilitate personalized learning experiences and foster innovation in business operations resonate strongly with younger generations (Giuggioli and Pellegrini, 2023). Entrepreneurs can conveniently and easily gain the essential skills to properly utilize AI tools using online self-learning platforms (Al-Doub *et al.*, 2008). These platforms include a diverse range of tools, such as lessons, interactive modules, and

immediate feedback, that can assist entrepreneurs in comprehending and applying AI in their firms (Campbell *et al.*, 2020). Entrepreneurs can keep themselves updated with the latest advancements in AI, customize their learning to suit their specific business needs, and apply their newly acquired knowledge to enhance efficiency and competitiveness (Al-Hunaiyyan *et al.*, 2021; Al-Hunaiyyan *et al.*, 2021D). Moreover, the incorporation of AI in small firms is inherently connected to improving individual leadership skills (Almonawer *et al.*, 2023) and innovative problem-solving (Al-Sharhan *et al.*, 2006). AI-powered solutions can improve mobile learning experiences by offering customized, context-sensitive, and adaptable learning possibilities (Al-Hunaiyyan *et al.*, 2021), which are essential for small business owners who aim to continuously educate themselves. From a Human-Computer Interaction (HCI) perspective, it is crucial to carefully design the usability, accessibility, and user experience of these AI tools for mobile platforms to cater to a wide range of user groups (Al-Hunaiyyan *et al.*, 2021C; Alhajri *et al.*, 2011).

Challenges of AI adoption in small businesses

Despite the potential benefits, several challenges hinder the adoption of AI in small businesses. Cost and resource limitations are often the most significant barriers, as implementing AI technologies can require substantial financial investments that small businesses may not be able to afford (Enholm *et al.*, 2021). Additionally, enterprises may lack the technical expertise to manage and utilize AI tools effectively, leading to an underutilization of the technology's potential. Ethical concerns, including data privacy and security, are also cited as challenges, particularly among students who may be more attuned to the social implications of technology. According to Holmes *et al.*, (2022), young adults express a strong need for transparency in how AI algorithms make decisions, especially regarding customer data handling and employee monitoring. In cultures where privacy is highly valued, such as in Kuwait, these ethical considerations are amplified, with students expressing reservations about the implications of data disclosure (Al-Kandari *et al.*, 2017). This reflects a broader societal concern and highlights the importance of establishing robust ethical frameworks to guide AI use in businesses. Literature identifies factors such

as budget constraints, lack of skilled workforce, data security concerns, and a perceived complexity of AI technologies as obstacles to widespread adoption (Chowdhury et al., 2022). Overcoming these challenges is critical for SMEs to fully harness the benefits of AI. Researchers (Boucher et al., 2022; Wallace, 2023) highlighted the importance of AI solutions being customizable and adaptable to the specific needs of SMEs. Tailoring AI applications to the industry and operational requirements of small enterprises ensures that these technologies align with the unique characteristics and challenges faced by smaller enterprises. Government support and policies, especially in Kuwait and probably Malaysia, are recognized as influential factors in fostering AI adoption among small businesses.

Cross-cultural comparisons of AI perceptions

Cultural context significantly influences students' perceptions of AI and its applicability in small businesses. For example, studies comparing students in Kuwait and Malaysia suggest that cultural attitudes toward innovation and technology adoption vary widely between the two regions (Albanay, 2024; Khalid, 2020). In contrast, Malaysian students tend to exhibit a more favorable view of AI's transformative potential, largely due to government initiatives promoting digital literacy and innovation. Malaysia's strong emphasis on Science, Technology, Engineering, and Mathematics (STEM) education and investment in digital infrastructure has created a generation of students more inclined to embrace AI and perceive its value for economic development (Lada et al., 2023). A study by Baabdullah et al., (2021) provides background on the importance of SMEs and AI in gaining a competitive advantage, leading to an investigation of AI practices in small businesses in Saudi Arabia. The study emphasized the importance of technology readiness, such as awareness and technical infrastructure, in the acceptance of AI practices (Ahmed, 2019). They demonstrated that the acceptance of AI practices significantly influenced customer AI-based interactions. They stress that it is important to extensively familiarize people with AI practices and increase awareness of their benefits and characteristics. They assert that education and training programs can help to raise the current level of awareness and the value generated from AI practices. Moreover, Lada et al., (2023) examine

the relationship between various factors and AI Adoption among small businesses in Sabah, Malaysia, highlighting the significance of Top Management Commitment and Organization Readiness in driving AI outcomes. Findings reveal that competitive pressure, employee adaptability, and external support do not have a significant impact on AI adoption in SMEs. The study emphasizes the importance of focusing on and enhancing top management commitment and organization readiness practices to improve AI outcomes in small enterprises. Several case studies and success stories highlight instances where small businesses have successfully implemented AI technologies. These cases illustrate how AI can be applied across various sectors, showcasing tangible benefits such as increased productivity, streamlined processes, and improved competitiveness. A questionnaire was made and sent to small businesses in South Africa by Boucher, Cullen, and Calitz (2022) to find out how they felt about the use of AI technologies by small businesses. Based on the answers of 295 people who answered, only 17% were positive about the use of AI and related technologies. The results also show that only 25% of those who answered think that new technologies could help small businesses. Their research gave new information about how small and medium-sized businesses think about and use AI and other new technologies. Furthermore, Wallace (2023) examined the impact of AI from the business owner's perspective. The study sheds light on the fear of AI and anxiety about its ubiquity, while realizing how it can be leveraged to stimulate improvement in entrepreneurship. The author discussed the fundamental understanding of the related areas of study that are important for small business entrepreneurs to navigate the uncertainty at the heart of this AI-driven seismic shift in the business landscape. (Mashat, 2020) examined the use of AI in small businesses across Saudi Arabia and assessed how AI knowledge and application impact advanced entrepreneurship. Surveying 204 small businesses—predominantly tech-oriented—in major Saudi cities. The study reveals a significant gap in both AI use and knowledge. This shortfall is shown to hinder entrepreneurial growth and creativity within the local market. The findings underscore a critical need for AI integration to enhance entrepreneurial capabilities among Saudi small businesses, thereby addressing a gap in the literature on technology-

Table 1: Sample distribution according to the demographic variables (834 students)

Variables		Frequency (F)	Percent %
Gender	Male	316	37.9
	Female	518	62.1
Country	Kuwait	401	48.1
	Malaysia	433	51.9

driven entrepreneurship in the Kingdom. According to Khalid (2020), the role of AI learning in enhancing entrepreneurial performance among university students in Malaysia focuses on how entrepreneurial orientation and strategic entrepreneurship facilitate this effect. The research also examines the moderating influence of government funding and students' attitudes towards entrepreneurship. A survey conducted with 500 teaching staff across Malaysian universities revealed that AI learning significantly boosts entrepreneurial outcomes. The study confirmed that entrepreneurial orientation and strategic entrepreneurship are crucial in linking AI learning to improved entrepreneurial performance. Moreover, Albanay (2024) explored the challenges, benefits, and practical steps for successful Kuwaiti SMEs with the country's vision towards digital transformation and knowledge economy. To achieve these objectives, a quantitative research approach was employed using a structured survey distributed to a total of 834 university students from Kuwait and Malaysia.

MATERIALS AND METHODS

Research methodology

This study employed a mixed-method approach, integrating quantitative survey data with bibliometric analysis. The methodology facilitates a comparative investigation of students' perspectives in two distinct national contexts (Kuwait and Malaysia), while situating the findings within the wider academic framework of AI and SME research.

Quantitative method

This research utilized a quantitative methodology to investigate college students' perspectives on AI in small businesses in Kuwait and Malaysia.

Sample

The target population consists of students from

higher education institutions, including business college students from Malaysia and Kuwait. The investigation comprised 834 students, with 401 from Malaysia and 433 from Kuwait. The demographic data and sample distribution of the study population are presented in Table 1.

Instrument

A 5-point Likert scale questionnaire was developed to assess the responses of students regarding various aspects of AI and its impact, especially for promoting small businesses. The survey was administered to a sample of 834 college students in Malaysia and Kuwait via an online platform. In addition to the demographic part, the questionnaire comprised 27 items organized into five categories: "awareness of AI, perceived benefits of AI, perceived impact of AI on small businesses, willingness to use AI, and challenges associated with AI". Each item in these sections was evaluated on a scale from 1 ("Strongly Disagree") to 5 ("Strongly Agree"), facilitating a nuanced comprehension of students' attitudes and preparedness to use AI. This quantitative research yields measurable data that indicates student awareness and perceptions, facilitating statistical comparisons between the two nations.

Analysis and data validation

The questionnaire was distributed electronically to the selected students. The data was subsequently collected electronically. Descriptive statistics, including frequencies, percentages, mean, and standard deviation, are utilized to interpret quantitative survey data. To ascertain any statistically significant difference between the means of two independent groups (namely, students from Kuwait and Malaysia), the independent-sample t-test is employed. Additionally, SPSS was utilized to calculate the correlation coefficients. The relationships between the individual aspects and the overall score

Table 2: Reliability statistics

	Group	N of Items	Cronbach's Alpha
A	AI Awareness	4	0.73
B	Perceived Benefits of AI	6	0.81
C	Perceived Impact of AI on SMEs	8	0.86
D	Willingness and Future Involvement with AI	3	0.74
E	Challenges	6	0.73
	Total	27	0.91

were significantly strong ($p < 0.01$). Similarly, the questionnaire's reliability was assessed by calculating Cronbach's alpha using SPSS. The questionnaire's dimensions demonstrate significant reliability, as indicated by the coefficient values in Table 2, which range from 0.73 to 0.86. The overall Cronbach's Alpha coefficient is 0.91. Consequently, the questionnaire applies to the foundational study sample, and the results can be deemed reliable.

Bibliometric analysis

A bibliometric analysis was conducted to examine research trends and developments in AI and SMEs. This bibliometric approach was designed to identify and analyze relevant academic publications during different periods for Kuwait and Malaysia, thus providing contextual insights into the progression of AI-related research in the SME sector. The methodology for the bibliometric analysis followed three main phases: data collection, data processing, and data analysis.

1. *Data collection*: The Scopus database was queried using a set of keywords related to AI and SMEs to capture a broad scope of publications. The search parameters were limited to articles, conference papers, book chapters, and review papers, initially yielding 112 documents.

2. *Data Processing*: A thorough screening was conducted to remove irrelevant or duplicate entries, resulting in a refined dataset for analysis. The documents were filtered based on relevance to AI applications within SMEs, ensuring that only pertinent publications were included for in-depth analysis.

3. *Data Analysis*: The final dataset underwent a comprehensive bibliometric analysis using MS-

Excel for descriptive statistics, BiblioMagika for mapping key publication metrics, and VOSviewer for constructing and visualizing bibliometric networks. Key variables, such as publication year, source type, author affiliations, citation counts, and keywords, were analyzed to identify significant research trends, frequently cited studies, and collaborative networks within the field.

RESULTS AND DISCUSSION

Results and findings

This section combines qualitative findings to thoroughly understand the students' views on AI technologies in business promotion, along with a bibliometric analysis that describes current research in the field concerning the study objectives.

Quantitative analysis

The subsequent subsections delineate and evaluate the findings of the questionnaire that investigates students' perceptions of AI in small enterprises. Table 3 offers an overview of students' perspectives, whereas Tables 4 to 8 give statistical data across five categories, analyzing the statistical differences between students from Kuwait and Malaysia. This group of factors is: "awareness of AI, perceived benefits of AI, perceived impact of AI on small businesses, willingness to use AI, and challenges associated with AI".

Students' perspectives on AI for small businesses

Table 3 suggests that students from both Kuwait and Malaysia hold similar and largely positive views on AI's role in small businesses. Across all five factors, the mean scores are consistently high (ranging from 3.90 to 4.08 on a 5-point scale), indicating overall

TABLE 3: STUDENTS' PERSPECTIVE OF AI FOR SMALL BUSINESSES: (SIGNIFICANT DIFFERENCES) - T-TEST

	Factor	Country	Students	Mean	SD	Mean	t	Significance
A	AI Awareness	Kuwait	401	3.90	0.539	3.90	0.040	0.97
		Malaysia	433	3.90	0.551			
B	Perceived benefits of AI.	Kuwait	401	4.07	0.514	4.07	0.155	0.88
		Malaysia	433	4.08	0.523			
C	Perceived impact of AI on small businesses.	Kuwait	401	4.05	0.493	4.05	0.204	0.84
		Malaysia	433	4.06	0.507			
D	Willingness to use, or future involvement with AI.	Kuwait	401	4.01	0.589	4.01	-0.333	0.74
		Malaysia	433	4.02	0.601			
E	Challenges of AI.	Kuwait	401	4.02	0.464	4.02	-0.105	0.92
		Malaysia	433	4.03	0.475			

Table 4: Students' awareness of AI (Frequency 834)

	Question	Gender	Students	Mean	SD	t	Significance
1	I am familiar with the concept of AI.	Kuwait	401	4.06	0.664	-0.004	0.99
		Malaysia	433	4.06	0.686		
2	I have experience using AI tools and applications.	Kuwait	401	3.80	0.719	0.071	0.94
		Malaysia	433	3.80	0.730		
3	I have experience using AI tools and applications.	Kuwait	401	3.97	0.746	-0.152	0.88
		Malaysia	433	3.98	0.760		
4	I have taken course/s or participated in activities related to AI during my studies.	Kuwait	401	3.77	0.762	-0.029	0.98
		Malaysia	433	3.77	0.770		

agreement and favorable perceptions regarding AI's awareness, benefits, impact, willingness to use, and challenges. The analysis of Table 3 reveals that students from both Kuwait and Malaysia hold similar and largely positive views on AI's role in small businesses. Across all five factors, the mean scores are consistently high (ranging from 3.90 to 4.08 on a 5-point scale), indicating overall agreement and favorable perceptions regarding AI's awareness, benefits, impact, willingness to use, and challenges. In addition, no statistically significant differences between students from Kuwait and Malaysia regarding their perspectives on AI and small businesses. For AI awareness, both groups reported identical mean scores of 3.90, with a p-value of 0.97, indicating no significant difference. Similarly, perceived benefits of AI showed means of 4.07 for Kuwaiti students and 4.08 for Malaysian students, with a p-value of 0.88, suggesting similar perceptions. The perceived impact of AI on small businesses had nearly identical means (Kuwait: 4.05, Malaysia: 4.06) and a p-value

of 0.84, confirming no statistical difference. In terms of willingness to use AI, the mean scores were 4.01 and 4.02 for Kuwait and Malaysia, respectively, with a p-value of 0.74, while the challenges associated with AI were rated at 4.02 and 4.03 for Kuwait and Malaysia, with a p-value of 0.92, again showing no significant variation. The consistently high p-values (all above the 0.05 threshold) across all factors demonstrate that the perspectives of students from both countries are statistically similar. This consistency in means and standard deviations suggests a shared understanding of AI's benefits, challenges, and potential applications for small businesses across the two groups. Future research could explore additional demographic or cultural factors that may influence these perspectives or focus on specific challenges in adopting AI within different regional contexts.

Awareness of AI

The analysis of Table 4 highlights the similarities in AI awareness between students from Kuwait and

TABLE 5: STUDENTS' PERCEIVED EFFECTIVENESS OF AI (FREQUENCY 834)

	Question	Gender	Students	Mean	SD	t	Significance
1	I believe that AI tools can contribute to the Automation of tasks.	Kuwait	401	4.16	0.699	-0.064	0.95
		Malaysia	433	4.17	0.710		
2	I believe that AI tools can contribute to better decision-making in entrepreneurship.	Kuwait	401	3.91	0.742	-0.157	0.88
		Malaysia	433	3.92	0.759		
3	I believe that AI tools can contribute to increasing Competition.	Kuwait	401	4.10	0.734	0.040	0.97
		Malaysia	433	4.10	0.744		
4	I believe that AI tools can contribute to Improved media design.	Kuwait	401	4.10	0.738	-0.253	0.80
		Malaysia	433	4.11	0.756		
5	I believe that AI tools can contribute to cost savings.	Kuwait	401	4.12	0.703	0.110	0.91
		Malaysia	433	4.11	0.708		
6	I believe that AI tools can contribute to enhancing efficiency.	Kuwait	401	4.02	0.694	-0.338	0.74
		Malaysia	433	4.03	0.710		

Malaysia based on their responses to four questions about their familiarity and experience with AI. The mean scores for all questions show minimal variation between the two groups, indicating comparable levels of awareness and engagement with AI tools and education (Al-Sharhan and Al-Hunaiyyan, 2012). For the question regarding familiarity with the concept of AI, both groups achieved an identical mean score of 4.06, with a t-value of -0.004 and a significance level of 0.99, demonstrating no statistical difference. Similarly, for experience using AI tools and applications, the mean scores for both groups were 3.80, with a t-value of 0.071 and a significance level of 0.94, again reflecting no significant variation. The question assessing further experience with AI tools yielded mean scores of 3.97 for Kuwaiti students and 3.98 for Malaysian students, with a t-value of -0.152 and a significance level of 0.88, confirming statistical similarity. Lastly, the question regarding participation in AI-related courses or activities showed identical mean scores of 3.77 for both groups, with a t-value of -0.029 and a significance level of 0.98, reinforcing the lack of significant difference. These results suggest a uniform level of awareness and exposure to AI among students from Kuwait and Malaysia, reflecting a shared understanding and interest in AI despite potential regional or cultural differences. This alignment underscores the global nature of AI awareness and its increasing integration into education systems across diverse contexts.

Perceived benefits of AI

Table 5 highlights students' perceived effectiveness of AI tools across six items, with data from both Kuwaiti and Malaysian students showing strikingly similar results. For the belief that AI tools can contribute to task automation, the mean scores were 4.16 for Kuwait and 4.17 for Malaysia, with a t-value of -0.064 and a significance level of 0.95, indicating no statistical difference. In terms of AI's role in better decision-making in entrepreneurship, both groups rated this highly, with means of 3.91 for Kuwait and 3.92 for Malaysia, yielding a t-value of -0.157 and a significance level of 0.88. The belief that AI tools enhance competition also showed identical mean scores of 4.10 for both groups, with a t-value of 0.040 and a significance level of 0.97. Regarding improved media design, Kuwaiti students scored 4.10 and Malaysian students 4.11, with a t-value of -0.253 and a significance level of 0.80, further confirming similarity. Cost savings also received high ratings, with means of 4.12 (Kuwait) and 4.11 (Malaysia), a t-value of 0.110, and a significance level of 0.91. Finally, for efficiency enhancement, the scores were 4.02 (Kuwait) and 4.03 (Malaysia), with a t-value of -0.338 and a significance level of 0.74. Across all six dimensions, the consistently high mean scores (ranging from 3.91 to 4.17) demonstrate strong agreement on the effectiveness of AI tools, while the consistently high p-values (all above 0.05) show no statistically significant differences between the two groups.

TABLE 6: STUDENTS' PERCEIVED IMPACT OF AI IN PROMOTING BUSINESSES (FREQUENCY 834)

	Question	Country	Students	Mean	SD	t	Significance
1	AI tools have the potential to enhance the efficiency of small business operations.	Kuwait	401	4.09	0.647	0.053	0.96
		Malaysia	433	4.09	0.659		
2	I believe that AI tools can contribute to better decision-making in entrepreneurship.	Kuwait	401	3.92	0.721	-0.077	0.94
		Malaysia	433	3.93	0.740		
3	I believe that AI tools can positively impact the promotion of small businesses.	Kuwait	401	4.07	0.669	-0.072	0.94
		Malaysia	433	4.08	0.687		
4	I believe that AI tools can make Innovation for SMEs.	Kuwait	401	4.08	0.771	-0.169	0.87
		Malaysia	433	4.09	0.784		
5	I believe that AI helps in cost-saving for SMEs.	Kuwait	401	4.05	0.754	-0.175	0.86
		Malaysia	433	4.06	0.770		
6	The use of AI tools is essential for the growth and success of small businesses.	Kuwait	401	4.02	0.702	-0.084	0.93
		Malaysia	433	4.02	0.724		
7	Artificial Intelligence has value in SMEs – Business.	Kuwait	401	4.12	0.637	-0.278	0.78
		Malaysia	433	4.14	0.655		
8	I trust AI to do the job and tasks for businesses	Kuwait	401	4.02	0.685	-0.346	0.73
		Malaysia	433	4.04	0.701		

These results underscore a shared understanding among students from Kuwait and Malaysia regarding AI's potential to automate tasks, improve decision-making, foster competition, enhance media design, reduce costs, and increase efficiency, reflecting global recognition of AI's transformative potential in diverse fields.

Perceived impact of AI on small businesses

The analysis of Table 6 reveals that students from Kuwait and Malaysia share remarkably similar perceptions of AI's impact on promoting businesses, particularly SMEs. Across all eight questions, the mean scores are consistently high (ranging from 3.92 to 4.14), reflecting strong agreement on the positive contributions of AI to business operations. The data show no statistically significant differences between the two groups for any of the questions, as all p-values exceed 0.05, indicating alignment in their views. For instance, both Kuwaiti and Malaysian students agree that AI tools enhance the efficiency of small business operations, with identical mean scores of 4.09 and a t-value of 0.053. Similarly, they believe AI contributes to better decision-making in entrepreneurship (Kuwait: 3.92, Malaysia: 3.93) and positively impacts business promotion (Kuwait: 4.07, Malaysia: 4.08), with negligible differences and non-significant t-values (-0.077 and -0.072, respectively). Students

also recognize AI's role in fostering innovation and cost savings for SMEs, with near-identical means (e.g., innovation: Kuwait: 4.08, Malaysia: 4.09; cost savings: Kuwait: 4.05, Malaysia: 4.06). Additionally, both groups strongly affirm that AI is essential for SME growth and success, has value in SME operations, and can be trusted for business tasks, as reflected in high means (e.g., value in SMEs: Kuwait: 4.12, Malaysia: 4.14; trust in AI: Kuwait: 4.02, Malaysia: 4.04). The consistent responses across countries suggest a shared recognition of AI's transformative potential in enhancing efficiency, innovation, cost-effectiveness, and overall business success. These findings provide a solid foundation for promoting AI adoption in SMEs through targeted educational and policy initiatives while highlighting the need to address any remaining scepticism or barriers to implementation.

Willingness to utilize AI

Table 7 presents an analysis of students' willingness to utilize AI, comparing the responses of Kuwaiti and Malaysian students across three key questions. The mean scores for both groups are very similar, indicating a shared interest in learning and using AI tools, pursuing careers related to AI, and planning to use AI in the future. For the first question, "I am willing to learn and use AI tools to support small business activities," the mean scores are 4.12

Table 7: Students' willingness to utilize AI (Frequency 834)

	Question	Gender	Students	Mean	SD	t	Significance
1	I am willing to learn and use AI tools to support small business activities.	Kuwait	401	4.12	0.672	-0.252	0.80
		Malaysia	433	4.13	0.691		
2	I see you pursuing a career or projects related to AI in the future.	Kuwait	401	3.95	0.739	-0.257	0.80
		Malaysia	433	3.96	0.747		
3	I plan to use AI or similar tools for my future.	Kuwait	401	3.95	0.767	-0.300	0.76
		Malaysia	433	3.97	0.779		

Table 8: Challenges of using AI for businesses (Frequency 834)

	Question	Gender	Students	Mean	SD	t	Significance
1	I have concerns about the adoption of AI tools that might lead to faulty decisions.	Kuwait	401	4.06	0.660	-0.004	1.00
		Malaysia	433	4.06	0.682		
2	I have Concerns about ethical considerations with the adoption of AI tools in small businesses.	Kuwait	401	3.90	0.675	-0.149	0.88
		Malaysia	433	3.91	0.688		
3	The cost of AI applications is a major challenge for small businesses considering their adoption.	Kuwait	401	3.94	0.746	0.276	0.78
		Malaysia	433	3.93	0.758		
4	I have Concerns about data security and privacy with the adoption of AI tools in small businesses.	Kuwait	401	4.07	0.740	-0.304	0.76
		Malaysia	433	4.09	0.752		
5	The complexity and difficulty of AI technologies are a major challenge for small businesses.	Kuwait	401	4.10	0.718	-0.058	0.95
		Malaysia	433	4.10	0.733		
6	Artificial intelligence could be dangerous for workers can causing Job Displacement.	Kuwait	401	4.05	0.734	-0.177	0.86
		Malaysia	433	4.06	0.743		

for Kuwaiti students and 4.13 for Malaysian students, with a t-value of -0.252 and a significance level of 0.80, showing no statistically significant difference. Similarly, for the question "I see myself pursuing a career or projects related to AI in the future," both groups scored almost identically, with means of 3.95 for Kuwaiti students and 3.96 for Malaysian students, resulting in a t-value of -0.257 and a significance of 0.80. Finally, regarding future use of AI, the scores were also very close, with Kuwaiti students averaging 3.95 and Malaysian students 3.97, a t-value of -0.300, and a significance level of 0.76, again showing no significant difference. These results suggest that students from both Kuwait and Malaysia exhibit a strong and similar willingness to engage with AI, whether for supporting small business activities, pursuing AI-related careers, or utilizing AI tools

in their future endeavors. The lack of significant statistical differences across all questions highlights a broad and shared acceptance of AI's potential and its integration into students' professional aspirations and future use, regardless of the country.

Challenges of using AI

Table 8 explores the challenges associated with using AI for businesses and other disciplines, comparing the responses of students from Kuwait and Malaysia across six key concerns. The results show that both groups share similar concerns regarding the adoption of AI tools, with no statistically significant differences between them, as indicated by high p-values above 0.05 for all questions. For the concern "I have concerns about the adoption of AI tools that might lead to faulty

Table 9: Citation metric table (Comparison of Kuwait and Malaysia)

Kuwait		Malaysia	
Main Information	Data	Main Information	Data
Publication Years	2018 - 2024	Publication Years	2010 - 2024
Total Publications	10	Total Publications	105
Citable Year	7	Citable Year	15
Number of Contributing Authors	36	Number of Contributing Authors	487
Number of Cited Papers	9	Number of Cited Papers	79
Total Citations	234	Total Citations	1,872
Citation per Paper	23.40	Citation per Paper	17.83
Citation per Cited Paper	26.00	Citation per Cited Paper	23.70
Citation per Year	39.00	Citation per Year	133.71
Citation per Author	6.50	Citation per Author	3.84
Author per Paper	3.60	Author per Paper	4.64
Citation sums within h-Core	232	Citation sums within h-Core	1,743
h-index	6	h-index	20
g-index	10	g-index	42
m-index	0.857	m-index	1.333

decisions,” both Kuwaiti and Malaysian students scored equally, with a mean of 4.06, a t-value of -0.004, and a significance of 1.00, suggesting no difference in their views. Similarly, concerns about ethical considerations in AI adoption were rated similarly by both groups (Kuwait: 3.90, Malaysia: 3.91), with a t-value of -0.149 and a significance of 0.88. Both groups also expressed concern over the cost of AI applications, with the mean scores being 3.94 for Kuwait and 3.93 for Malaysia, a t-value of 0.276, and a significance of 0.78, indicating no significant difference. Regarding data security and privacy issues, both groups scored similarly (Kuwait: 4.07, Malaysia: 4.09), with a t-value of -0.304 and a significance of 0.76. The complexity and difficulty of AI technologies were also seen as a challenge by both groups, with equal mean scores of 4.10 (Kuwait and Malaysia), a t-value of -0.058, and a significance of 0.95, further demonstrating a shared concern. Lastly, concerns about AI causing job displacement were also similar, with Kuwaiti students scoring 4.05 and Malaysian students scoring 4.06, a t-value of -0.177, and a significance of 0.86. Overall, these findings suggest that both Kuwaiti and Malaysian students have similar concerns regarding AI adoption in businesses, with the primary challenges being the potential for faulty decisions, ethical issues, costs, data security, complexity, and job displacement. The lack of statistical differences highlights a common

global awareness of the barriers to AI integration in small businesses.

Bibliometric analysis

Based on Table 9, the field of AI and business research has seen unprecedented growth in Kuwait and Malaysia. A bibliometric comparison of Kuwait and Malaysia reveals several differences in publication productivity, author collaboration, and citation impact. Malaysia’s research foray in AI and business had a time frame from 2010 to 2024. This suggests a longer-term research initiative. In contrast, Kuwait’s participation in this field was more recent, with a time frame ranging from 2018 to 2024. Malaysia has produced 105 papers as compared to Kuwait’s 10 publications. This reflects that Malaysia has a more established research presence in the field of AI. This disparity suggests that AI and business are newer areas of focus for Kuwait. Author contributions also differ greatly. Kuwait has 36 contributing authors, whereas Malaysia has 487, highlighting a stronger research network in Malaysia, fostering collaboration and dynamic research. Additionally, Malaysia has 79 cited papers versus Kuwait’s nine, indicating broader recognition and impact. In total citations, Malaysia again leads with 1,872 compared to Kuwait’s 234. Despite a lower citation count, Kuwait’s average citations per paper (23.4) surpass Malaysia’s (17.83),

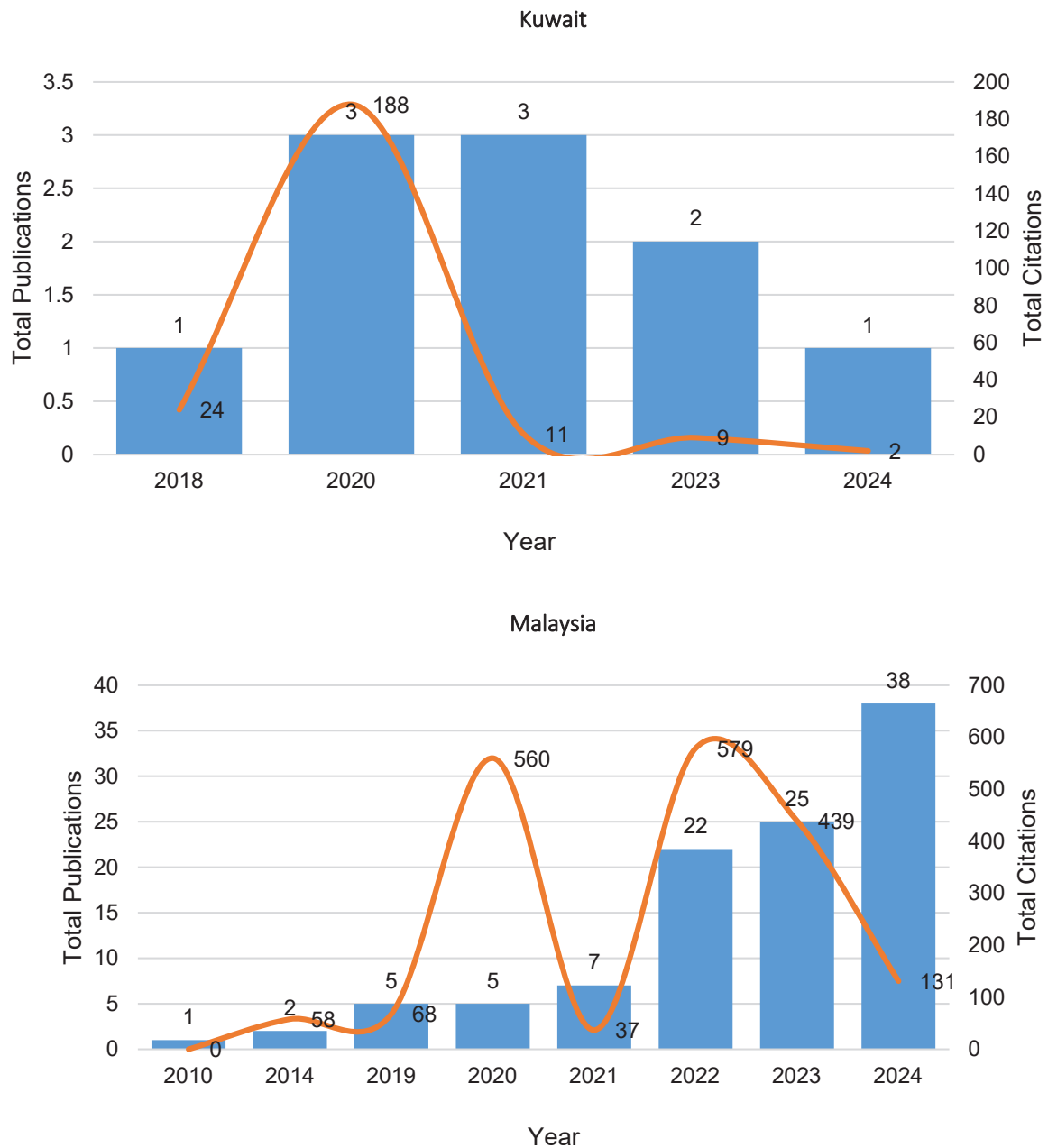


Fig. 1: Total Publications Productivity and Citations (Comparison Kuwait- Malaysia)

suggesting that Kuwait's studies have a high impact, possibly indicating a focus on quality. Similarly, Kuwait's citations per cited paper (26) are slightly higher than Malaysia's (23.7), emphasizing that its limited output still commands attention. These findings reveal that Malaysia demonstrates a more expansive and collaborative research environment,

supported by higher publication and citation counts, establishing it as a key contributor. Although newer to the field, Kuwait shows a promising impact per paper, underscoring its emerging potential in AI and business research.

Referring to Fig. 1, the comparison of AI and business research output and citations between

Kuwait and Malaysia highlights distinct trends in productivity and impact over the years. Kuwait's research activities in this field began in 2018, with an initial publication yielding 24 citations. The country reached its peak in 2020, both in publication count and citation impact, with three publications generating a significant 188 citations. This year marked Kuwait's highest research influence within the field. However, following 2020, Kuwait experienced a notable decline in citation impact, even though it continued to publish two to three papers annually in subsequent years. In 2024, Kuwait's research output had reduced to a single publication. This was followed by only two citations, indicating a drop in both productivity and impact. In contrast, Malaysia has exhibited a longer timeline in AI and business research. Beginning in 2010, Malaysia initially experienced a low research output with fewer than five publications annually until 2019. After this period, Malaysia's research activity improved tremendously in subsequent years, with two peaks in citation impact. The first citation peak took place in 2020, with five publications amassing 560 citations. The second citation impact occurred in 2022, with 22 publications and 579 citations. This trend suggests a growing influence of Malaysian research. In contrast to Kuwait, Malaysia's productivity grew steadily and produced 38 publications by 2024. Despite a citation drop from 579 in 2022 to 181 in 2024, the publication productivity remained on an upward trend. This data reveals that Malaysia has a growing research presence in AI and business. Kuwait, on the other hand, has conducted a more modern, yet smaller-scale, research. This suggests that Kuwait's research productivity and impact are seen in a certain time frame only, differing from Malaysia's productivity in publication and influence, which has been more consistent.

CONCLUSION

This study discusses significant insights into the students' views of AI's function in small businesses in Kuwait and Malaysia, uncovering both universal themes and region-specific dynamics. The results indicate a widely held favorable perspective among students in both countries concerning the advantages of AI for small businesses, including improved efficiency, innovation, and cost reduction.

The results also reveal common apprehensions among students in both nations concerning ethical issues, data privacy, the intricacies of AI technology, and the risk of employment displacement. These problems highlight the necessity for focused educational programs and regulatory structures to alleviate concerns and promote confidence in using AI. The lack of statistically significant differences in opinions indicates that students from these varied cultural and economic backgrounds possess a shared grasp of AI's potential. This alignment highlights the worldwide significance of AI, as technical progress surpasses regional and cultural limitations. Nonetheless, disparities in the historical and strategic contexts of AI adoption and development are apparent through bibliometric analysis. Malaysia's prior and more comprehensive engagement in AI research, bolstered by strong governmental regulations and collaborative initiatives, establishes the nation as a frontrunner in AI innovation. Its holistic approach encompasses various fields, demonstrating a sophisticated and integrated research environment. Kuwait's burgeoning yet impactful research in specific AI applications indicates a focused strategy with considerable potential. Kuwait's research output is very low relative to Malaysia; nonetheless, its superior citations per manuscript underscore the quality and significance of its contributions in specialized fields. This study's findings support and enhance current research about perceptions and adoption of AI in small enterprises, offering detailed insights into cross-cultural dynamics. According to previous research, students from Kuwait and Malaysia exhibited a common positive perspective on AI's capacity to improve operational efficiency, assist in decision-making, and promote innovation in SMEs. These parallels with wider trends in AI acceptance are documented in the literature, indicating that younger, technologically adept people are typically more receptive to the adoption of new technologies (Senadjki *et al.*, 2023). The absence of statistically significant variations in beliefs between Kuwaiti and Malaysian pupils indicates that factors like global exposure to technology and education, rather than national distinctions, may influence these attitudes. Research such as that conducted by Khalid (2020) indicates that digital globalization has diminished the

perceptual disparity among nations, promoting a more cohesive comprehension of AI's potential. This corresponds with the findings, suggesting that despite Malaysia's more developed AI ecosystem, both student groups exhibit similar awareness and enthusiasm for AI implementation in SMEs. The findings indicate that Kuwait has the potential to enhance its AI research environment through international cooperation, especially with prominent leaders such as Malaysia. Kuwait's specific strategy may be augmented by extensive research and development projects, thereby strengthening its position in the global AI arena. Conversely, Malaysia can enhance its present AI infrastructure by cultivating regional alliances to investigate new applications and reinforce its leadership in AI integration. These conclusions have significant ramifications for academia, legislation, and commercial practices. Customized academic programs can provide students with the skills required to address AI-related difficulties in SMEs and facilitate AI adoption. Policymakers in both nations can leverage these findings to build plans that tackle shared difficulties while utilizing distinct advantages. The collective positive views of AI among business practitioners indicate a promising opportunity for the incorporation of AI into small business operations, provided that adequate support and ethical considerations are established. The bibliometric analysis highlights Malaysia's prominence in AI and business research, marked by a substantial quantity of collaborative and multidisciplinary contributions. Malaysia's strong digital infrastructure and government-driven efforts have fostered an advanced research ecosystem. This aligns with research by [Lada et al., \(2023\)](#), which emphasizes the significance of national strategy in promoting AI development and integration. Kuwait's burgeoning yet significant contributions underscore its strategic emphasis on Vision 2035, which stresses technology-driven economic diversification ([Albanay, 2024](#)). This focused strategy, albeit yielding fewer publications, has significant relevance and impact, evidenced by Kuwait's superior average citations per work. The common issues highlighted in this study, including data security, ethical considerations, and employment displacement, are likewise evident in the literature. ([Holmes et al., 2022](#)) underscore that the ethical dilemmas and

workforce ramifications of AI implementation persist as significant obstacles to its widespread acceptance. Students in both nations express worries regarding the expense and intricacy of AI technology, which corroborates the findings of [Chowdhury et al. \(2022\)](#), who identify resource limitations as a major barrier for SMEs in the adoption of AI tools. The study's findings notably contradict the notion that Malaysian students would demonstrate more favorable attitudes toward AI, attributable to their nation's strong infrastructure and research ecosystem. This indicates that exposure to AI technologies within the school curriculum, as opposed to wider national disparities, may be a more critical factor influencing student attitudes. These findings present multiple ramifications for the academic community and policymakers. For example, broadening access to interdisciplinary AI education, as proposed by scholars like [Davenport and Ronanki \(2018\)](#), could alleviate students' collective apprehensions over AI's intricacy. Moreover, promoting international collaborations between nascent and established AI ecosystems, exemplified by Malaysia and Kuwait, could facilitate knowledge exchange and talent enhancement. The study highlights the necessity for policymakers to establish comprehensive AI adoption frameworks that tackle prevalent issues, including ethical considerations, financial implications, data security, and employment displacement. This corresponds with the worldwide initiative for responsible AI integration, acknowledging the distinct developmental paths of nations such as Kuwait and Malaysia. Malaysia's leadership in collaborative AI research can exemplify Kuwait's focused, high-impact strategy, promoting cross-cultural encounters and the co-development of AI policies. The study underscores the necessity of incorporating AI instruction within university curricula, especially within business and entrepreneurship degrees. The report underscores the necessity for business practitioners to confront practical obstacles to AI adoption, including complexity and expense, while also highlighting its advantages in automation, decision-making, and innovation. This comprehension can inform the creation of AI solutions customized for small enterprises, guaranteeing more efficient execution and enhanced adoption. This study demonstrates the global

significance of AI in small businesses while also emphasizing regional variations in AI research and implementation tactics. Connecting the findings with current literature reveals that a balanced strategy—integrating focused, high-impact research with extensive, collaborative initiatives—can optimize AI’s capacity to foster sustainable growth in small enterprises. These observations emphasize the necessity of promoting education, collaboration, and supportive legislation to guarantee responsible and effective AI integration. Based on the findings of this study, the following practical recommendations are proposed to support the integration of AI in SMEs through educational, institutional, and governmental initiatives:

1. *Integrate AI training in business curricula:* Educational institutions should embed AI-related modules into business and entrepreneurship programs to enhance student preparedness and digital literacy.

2. *Establish AI innovation hubs:* Universities and incubators in Kuwait and Malaysia should create AI innovation centers where students and SME owners can co-develop practical solutions.

3. *Subsidize AI adoption for SMEs:* Governments should offer financial support or tax incentives to SMEs that invest in AI tools, especially in sectors with high innovation potential.

4. *Launch public-private AI mentorship programs:* Encourage partnerships between tech firms and SMEs to facilitate skill transfer, tool implementation, and sustainability.

5. *Develop national AI awareness campaigns:* Increase public understanding of AI through targeted campaigns, focusing on real-world success stories, particularly for micro and small businesses.

AUTHOR CONTRIBUTIONS

First Author: Conceived and developed the main research idea; led the conceptual framework and theoretical underpinnings; conducted the comprehensive literature review; designed the methodology; performed the primary data analysis; and took the lead in writing the original manuscript draft. Second Author: Assisted in refining the research design; contributed to data collection and preprocessing; provided critical feedback during the analysis phase; and participated in manuscript review and editing. Third Author: Supported

data interpretation and visualization; ensured methodological rigor through validation checks; contributed to the structuring of the results section; and assisted in manuscript revisions. Fourth Author: Oversaw overall project administration; facilitated access to resources and data; provided guidance on aligning the study with current scholarly debates; and contributed to the final review and editing of the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

AI	Artificial Intelligence
MDEC	Malaysia Digital Economy Corporation
MyDIGITAL	Malaysia Digital Economy Blueprint
NLP	Natural Language Processing
SMEs	Small and Medium-Sized Enterprises
STEM	Malaysia's strong emphasis on Science, Technology, Engineering, and Mathematics

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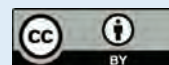
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ORIGINAL RESEARCH PAPER

Bridging the gap in public housing delivery: Evaluating awareness, accessibility, and affordability in government-funded estates

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ABSTRACT

BACKGROUND AND OBJECTIVES: Globally, public housing delivery faces persistent challenges in meeting the growing demand for affordable and accessible housing. Despite several national interventions, the gap between policy intent and housing outcomes remains significant. This study aimed to evaluate the effectiveness of government-funded housing delivery by examining levels of awareness, accessibility, affordability, and associated financial burdens among residents of public housing estates in Ogun State, Nigeria.

METHODS: An evaluative research design incorporated both primary and secondary data. The study population comprised residents of fully completed and occupied federal housing estates. A systematic sampling technique selected 134 housing units from a sampling frame of 1,337. Data were gathered through structured questionnaires and direct observations and were analysed using descriptive statistics and Pearson correlation at a 0.05 significance level.

FINDINGS: Among the respondents, 67% reported awareness of the housing delivery initiative, while 52% indicated that housing units were difficult to access. 47.5% perceived the housing units as expensive, and 22.5% rated them as very expensive. The financial burden was notably high, with power supply (AMS = 4.47), housing costs (AMS = 4.25), and water provision (AMS = 4.23) ranked as top cost concerns. Significant correlations were observed between housing costs and water provision ($r = .994$, $p = .001$), power supply ($r = .992$, $p = .001$), and transport to work ($r = .970$, $p = .006$). Furthermore, 38.5% of residents rated the housing environment as poor, while 46.8% described internal road infrastructure as poor.

CONCLUSION: The findings revealed substantial gaps in the design and implementation of public housing delivery programs, with issues of affordability, accessibility, and infrastructure maintenance contributing to financial stress among residents. Stronger political will, targeted subsidies, improved infrastructure, and inclusive publicity strategies are required to enhance housing outcomes and ensure that housing delivery is equitable, affordable, and sustainable.

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INTRODUCTION

Globally, housing units are known to be inadequate and deficient and probably need adjustment (Igwe *et al.*, 2017; Nubor, 2017; Ibimilua & Ibitoye, 2015). However, housing promotes human welfare, social life, economic growth, the health of the community, and various other aspects of human life (Ocholi, 2015). Housing and its environment are areas of concern to urban planners, and despite the numerous policy formulations in Nigeria, little or no improvement has been seen in recent times. In Nigeria, one of the major problems facing housing delivery processes is the continuously rising cost of building materials. This led to a great decrease in construction activities and numerous abandoned housing projects (public and private), which deterred the nation's socio-economic development. However, the Federal government tried to reduce this effect by creating the Nigeria Building and Road Research Institute (NBRRI) to encourage the utilisation of indigenously sourced building materials. Yet, the effort has not produced many results. Houses are still unaffordable due to the inability of the construction industry to utilise locally made (inexpensive) materials. This affected the achievement of the targets set in previous housing policies and programmes in Nigeria (Igwe *et al.*, 2017; Ibimilua & Ibitoye, 2015). Several studies have shown that many developing countries, including Nigeria, need millions of housing units to meet housing demands (Odekunle *et al.*, 2023; Abidin *et al.*, 2019; Aribigbola & Ayeniyo, 2012; UN-Habitat, 2012). The failure of the public sector to meet the increasing demand for housing in Nigeria is a major concern, and the explanations have been widely documented (Fakere *et al.*, 2020; Morakinyo *et al.*, 2014). Abidin *et al.*, (2019) described housing problems in Nigeria as qualitative and quantitative, in which both descriptions failed to satisfy the basic needs of the residents/citizens. Over the years, efforts to solve these housing problems (qualitative and quantitative problems) in Nigeria have led to a series of strategies and policies to make decent and affordable housing available for all citizens. However, these strategies and policies produced insignificant positive results in developing public housing in Ogun State, Nigeria. Also, most public housing estates/schemes are characterised by deficiencies in infrastructural facilities and utilities (Babalola *et*

al., 2016; Morakinyo *et al.*, 2014). Another gap lies in the low public awareness regarding available government-funded housing initiatives. Many intended beneficiaries are unaware of such schemes or lack clear information on applying and qualifying. Studies have shown that inadequate information dissemination and limited engagement with target populations hinder effective participation in public housing programs (Ibem & Amole, 2012; 2010). Additionally, accessibility to public housing is often marred by political patronage and corrupt practices. These factors disproportionately affect vulnerable groups, including the urban poor, who are ostensibly the primary targets of such interventions. Accessibility is further limited by physical location, lack of social amenities, and exclusionary planning processes (UN-Habitat, 2011). Perhaps most significantly, affordability remains a persistent barrier, as many housing units labelled "affordable" are priced far beyond the reach of low-income earners (Ibem & Amole, 2012). A mismatch between income levels and housing costs has been widely documented, particularly in urban areas with high land and construction costs (UN-Habitat, 2020; Olotuah, 2010; Ajanlekoko, 2001). Moreover, government housing projects often fail to align with the socio-economic realities of their intended beneficiaries, thereby contributing to under-occupancy or abandonment (Olotuah, 2010). It is important to state that the high cost of living in Ogun State, Nigeria, and the high cost of construction materials are partly responsible for the present low rate of housing provision, including the disrepair of existing buildings and their deterioration. Fakere *et al.*, (2020) and Bello (2019) observed that most of the Federal government's contributions to housing provision failed largely due to the secrecy and bureaucracy in the delivery processes. This indicates a need to conduct an empirical investigation and evaluation of the Federal government's contributions to housing provision, prompting this study's need in Ogun State, Nigeria. In light of these challenges, this study evaluates the Federal government housing delivery to examine the level of awareness, accessibility, affordability, and financial burden of the Federal government housing provisions to the populace. The study was conducted in four selected Federal housing estates, Olomore, Elegu, Ikoto, and Batoro, across the urban centres in Ogun State, Nigeria, from 2024 to 2025.

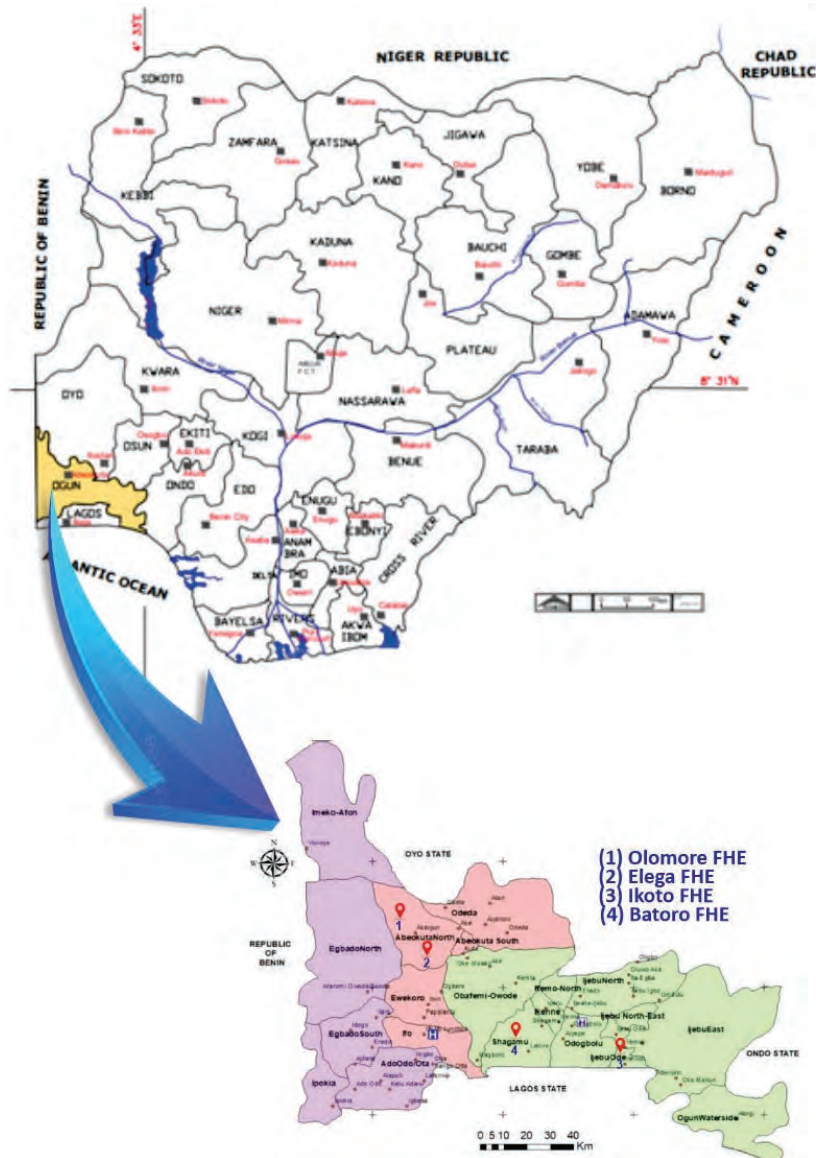


Fig. 1: Location of the study area

The study area

Ogun State is one of the six (6) states in southwestern Nigeria, created on February 3rd, 1976, from the former Western State. The State is contained within longitudes $2^{\circ} 45'E$ and $4^{\circ} 45'E$; and latitudes $6^{\circ} 15'N$ and $7^{\circ} 55'N$ (Olatunji, 2016). It is bounded on the west by the Republic of Benin, to the south by Lagos State, to the east by Ondo State, and the north by Oyo State (Fig. 1). Presently, the State is experiencing a great influx of both humans and traffic

as a result of its proximity to Lagos State (Fig. 1), one of the most populated cities in the Southern Sahara, the African continent. Hence, there is a high demand for decent housing and its ancillary facilities and/or utilities in the State capital and other major towns (Bello & Arowosegbe, 2014). This indicates that the effectiveness of federal housing policies in addressing the financial burden of housing is at stake in Ogun State. However, the State has a total of seventeen (17) Federal Housing Estates (FHEs); out of which only

four (4) estates - Olomore FHE in Abeokuta, Elegu FHE in Abeokuta, Ikoto FHE in Ijebu Ode, and Batoro FHE in Sagamu - were fully completed and occupied.

Conceptual/theoretical framework and literature review

Housing is an important indicator for evaluating the well-being of a nation's citizens and residents (Adriaanse, 2007). Several studies on government housing evaluation (Bello, 2019; Irouke, 2017; Babalola *et al.*, 2016; Jiboye, 2010) focused on awareness of housing provision, accessibility to decent housing, and affordability. Sufficient land must be accessible to meet the growing demand for housing, particularly in urban areas. The availability of suitable land parcels for residential development is vital for ensuring an adequate supply of housing units. Land availability also significantly influences housing affordability (Bello *et al.*, 2016). The costs associated with land acquisition and development directly impact the final price of housing units. When land availability is limited, land prices tend to rise, making it more difficult to provide affordable housing options. Therefore, ensuring the availability of sufficient land at reasonable costs is essential for promoting affordable housing initiatives (Fakere *et al.*, 2018). Housing accessibility refers to how individuals or households can easily obtain and afford suitable housing that meets their needs (Ocholi, 2015). It encompasses various dimensions, including physical accessibility, affordability, and inclusivity (Nubor, 2017; Ocholi, 2015; Ibimilua & Ibitoye, 2015). Physical accessibility refers to the availability of housing options that are designed and built to accommodate people with diverse abilities. It involves the removal of barriers and difficulties in acquiring housing units, especially public housing provision (Bello *et al.*, 2016), to ensure that individuals (including people with disabilities or mobility challenges) can access decent housing. This concept intersects with issues of income distribution and social equity. It involves addressing disparities in access to suitable housing based on income, race, ethnicity, gender, or other social factors (Bello, 2019; Ibem & Amole, 2012). It aims to promote equal opportunities and ensure that housing options are available to all members of society, regardless of their socio-economic backgrounds. Similarly, housing accessibility is influenced by government regulations

and policies (Baig & Sarwar, 2024; Moreno-Monroy *et al.*, 2020; Nesslein, 2002; Bello, 2019). Governments play a vital role in establishing and enforcing building codes, zoning regulations, and housing policies that promote accessibility and affordability. Policies related to rent control, subsidies, and incentives for affordable housing developments can significantly impact housing accessibility. Also, social and supportive housing initiatives cater to individuals or households with specific needs, such as low-income families, the homeless, or individuals with mental health issues. These housing programmes provide affordable and supportive services to improve housing stability and well-being (Blair & Larsen, 2010). Housing accessibility requires a multifaceted approach that addresses physical, financial, and social barriers. Collaboration among policymakers, urban planners, housing developers, and community organisations is crucial in creating inclusive housing options that are affordable, physically accessible, and socially equitable (Arunobi *et al.*, 2017; Igwe *et al.*, 2017). By focusing on housing accessibility, every government can foster sustainable and inclusive environments where everyone can access safe, suitable, and affordable housing. Housing decency refers to the condition and quality of housing that meets basic standards for human habitation (Fakere *et al.*, 2018; Ibem *et al.*, 2015). It encompasses various factors related to the physical, functional, and environmental aspects of housing. Housing decency is based on recognizing that safe, secure, and healthy living conditions are essential for individuals and communities to thrive (Bello, 2019). This concept entails providing sufficient living space for occupants (Ibem *et al.*, 2015). This includes appropriate room sizes, layout, and functionality to accommodate the needs of individuals or households. Adequate space ensures privacy, comfort, and the ability to carry out daily activities within the home. Also, housing should be structurally sound and free from significant structural defects or hazards. This includes the stability and integrity of the building, foundation, walls, roof, and other structural components. Structural soundness ensures the safety and well-being of occupants, protecting them from the risk of collapse or other structural failures. Housing decency encompasses safety and security considerations (Kolawole, 2015). It should have safety features such as fire exits, smoke detectors,

and secure locks. Adequate lighting and the absence of physical hazards within the premises are important for ensuring a safe living environment. It involves proper ventilation to ensure adequate airflow and good indoor air quality. Adequate ventilation helps prevent the accumulation of pollutants, moisture, and mould, which can adversely affect occupants. Natural lighting and access to fresh air are also important for creating a pleasant living environment (Kale, 2014; Aribigbola & Ayeniyo, 2012). Local building codes, regulations, and standards influence it. Compliance with these regulations ensures that housing meets minimum safety, health, and structural requirements. Governments play a crucial role in establishing and enforcing these standards to protect the rights and well-being of housing occupants (Arunobi *et al.*, 2017). However, promoting housing decency requires a combination of effective policies, enforcement mechanisms, and public awareness. Governments, housing authorities, and community organisations work together to ensure the availability of decent housing options and address substandard housing conditions, especially in developing countries (Igwe *et al.*, 2017; Aribigbola & Ayeniyo, 2012). Housing affordability refers to the ability of individuals or households to secure and maintain housing that meets their needs without experiencing excessive financial burden (Bello, 2019; Blair & Larsen, 2010). It involves balancing housing costs and household income, ensuring that housing expenses are within reasonable limits. However, housing affordability is crucial to housing accessibility (Haffner & Hulse, 2021; Li, 2015). It pertains to the cost of housing in relation to individuals' or households' income levels. Affordable housing should ideally require a reasonable portion of a household's income, leaving enough resources for other essential needs (Irouke, 2017). Ensuring housing affordability is essential to prevent housing cost burdens, where a significant portion of income is allocated to housing expenses, potentially leaving individuals or families financially strained (Iwedi & Onuegbu, 2014). This concept is often assessed based on the housing cost burden, which measures the proportion of household income allocated to housing expenses. Housing expenses typically include mortgage or rent payments, utilities, property taxes, and insurance. When housing costs consume a large percentage of household income, individuals or families may experience housing cost

burdens, leading to financial stress and limited resources for other essential needs. The affordability of housing is closely tied to household income levels. For housing to be affordable, the cost should be proportional to the income of individuals or households (Bello, 2019). Low-income households often face greater challenges accessing affordable housing due to limited financial resources. Affordable housing initiatives aim to bridge the gap between housing costs and income levels, ensuring that housing is within reach for individuals and families across the income spectrum (Bello *et al.*, 2016). Housing affordability is influenced by market dynamics, including supply and demand forces, construction costs, land prices, and interest rates. In areas where housing supply is limited or demand is high, housing prices tend to rise, making it more challenging for individuals and families to find affordable housing options (Iwedi & Onuegbu, 2014). Economic factors, such as inflation and income growth rates, also impact housing affordability (Irouke, 2017). Similarly, it is influenced by location, as housing costs vary across different areas. Urban areas and regions with high demand often have higher housing costs, making affordability a significant challenge. Additionally, transportation costs should be considered in the affordability equation, as living in more affordable areas farther away from job centres may result in higher commuting expenses (Rao *et al.*, 2023; Makarewicz *et al.*, 2020; Morakinyo *et al.*, 2014). Governments at various levels are critical in addressing housing affordability through policies and programmes. These may include rent control regulations, housing subsidies, tax incentives, and public housing initiatives. Governments can also implement inclusionary zoning, which requires developers to include affordable housing units in their projects, ensuring a mix of affordable and market-rate housing options (Blair & Larsen, 2010). Wiesel *et al.* (2023), Dong (2018), Albouy *et al.* (2016), and Dewilde & Lancee (2013) stated that income inequality exacerbates housing affordability challenges, as lower-income households struggle to access affordable housing. Affordability gaps emerge when housing costs outpace income growth, resulting in disparities between housing prices and household financial capabilities. Promoting housing affordability requires a comprehensive approach involving a combination of market interventions, government

Table 1: Sample size for the study

Federal housing estate	Housing units	
	Population	Sample size (10%)
Olomore Federal Housing Estate, Abeokuta	323	32
Elega Federal Housing Estate, Abeokuta	550	55
Ikoto Federal Housing Estate, Ijebu-Ode	230	23
Batoro Federal Housing Estate, Sagamu	234	24
Total	1,337	134

Source: Federal Ministry of Works and Housing (FMWH) (Ogun state field office), and authors' computation (2025)

policies, and social initiatives (Baig & Sarwar, 2024). Collaboration among policymakers, developers, community organisations, and financial institutions is crucial to developing and implementing strategies that ensure a sufficient supply of affordable housing options and address the needs of individuals and families across income levels. Various indices and metrics are used to measure housing affordability, such as the Housing Affordability Index (HAI) or the Price-to-Income Ratio (PIR). These indices compare housing costs to household income levels and provide a quantitative measure of affordability. They help policymakers, researchers, and housing stakeholders assess affordability trends and identify areas where intervention is needed (Morakinyo et al., 2014).

MATERIALS AND METHODS

The study utilised an evaluative research design incorporating primary and secondary data sources. This was systematically adopted to assess the awareness, accessibility, affordability, and financial burden of the Federal government's initiatives to address housing demand in Ogun State, Nigeria. Primary data were collected through questionnaires and direct observations. In contrast, secondary data were sourced from the Federal Ministry of Works and Housing (Ogun State field office), Google Earth, Geographic Information Systems (GIS), Ogun State Ministry of Physical Planning & Urban Development, and relevant journals, books, and theses. The population of interest for this study was the residents (occupiers of the housing units) of the four (4) FHEs, Olomore FHE in Abeokuta, Elega FHE in Abeokuta, Ikoto FHE in Ijebu Ode, and Batoro FHE in Sagamu, that were fully completed and occupied in Ogun State, Nigeria. A systematic sampling technique was employed to select a sample size of 10% of the target population, which provided a sample size of 134 housing units for the study (Table 1). The data

collected were analysed using both descriptive and inferential statistical methods.

RESULTS AND DISCUSSIONS

The socio-economic characteristics of the residents

The study revealed that the majority of the residents (occupiers of the housing units) of Federal housing estates in Ogun State were males (67.2%), married (71.7%), and occupied as public/civil servants (54.5%); with an average age of 49 ± 10 years, and a monthly income of $\text{N}139,400:00 \pm \text{N}37,205:00$ (Table 2). It implies that most of the residents in the Federal housing estates were public/civil servants (males) within the active age of the society, meaning that public/civil servants were the major occupiers of Federal housing units in Ogun State, Nigeria. This corroborates the findings of Ibem & Amole (2010), who argued that public servants are the major beneficiaries of federal housing programs; hence, denying the vulnerable groups (urban poor) access to public housing.

Awareness of federal housing delivery

The study examined the awareness of Federal housing delivery in Ogun State, Nigeria. Most residents (occupiers of the housing units) were aware of the housing provisions because they were civil/public servants (Table 2). Specifically, 67% of the residents reported being aware of the Federal housing delivery. In comparison, 33% indicated they were unaware (Fig. 2). The latter group mentioned that they occupied or possessed their housing units through a transfer of ownership. Additionally, the study found that the cost of securing housing units in the coverage areas tends to increase gradually during the transfer of ownership process. This suggests that land or housing speculation within the Federal housing estates contributes to rising housing units and land costs over time (Nubor, 2017; Bello & Arowosegbe, 2014).

Table 2: Socio-economic characteristics of the residents

Gender	Frequency	%	Cumulative (%)
Male	90	67.2	67.2
Female	44	32.8	100.0
Total	134	100	
Age	Frequency	%	Cumulative (%)
18-30years	4	3.0	3.0
31-40years	31	23.1	26.1
41-50years	56	41.8	67.9
51-60years	34	25.4	93.3
> 60years	9	6.7	100.0
Total	134	100	
Marital status	Frequency	%	Cumulative (%)
Single	5	3.7	3.7
Married	96	71.7	75.4
Widow(er)	18	13.4	88.8
Divorced	9	6.7	95.5
Separated	6	4.5	100.0
Total	134	100	
Occupation	Frequency	%	Cumulative (%)
Public/Civil Servant	73	54.5	54.5
Private Employee	29	21.6	76.1
Artisan	5	3.7	79.8
Trader	17	12.7	92.5
Farmer	4	3.0	95.5
Retiree	6	4.5	100
Total	134	100	
Monthly income	Frequency	%	Cumulative (%)
Less than ₦50,000	5	3.7	3.7
₦50,000 – ₦100,000	27	20.2	23.9
₦101,000 – ₦150,000	61	45.5	69.4
₦151,000 – ₦200,000	33	24.6	94.0
Above ₦200,000	8	6.0	100
Total	134	100	

Source: Authors' field survey, 2025.

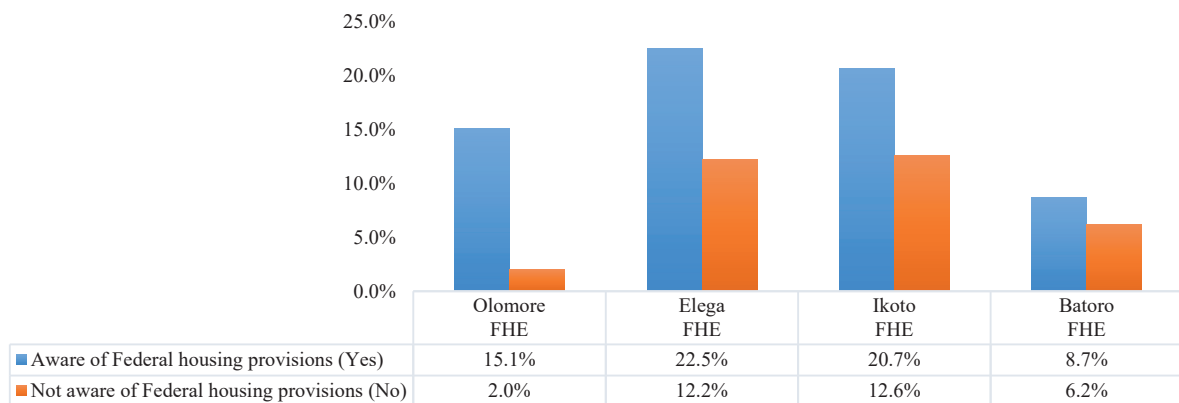


Fig. 2: Awareness of federal housing provisions (Source: authors' fieldwork, 2025).

Gaps in public housing delivery

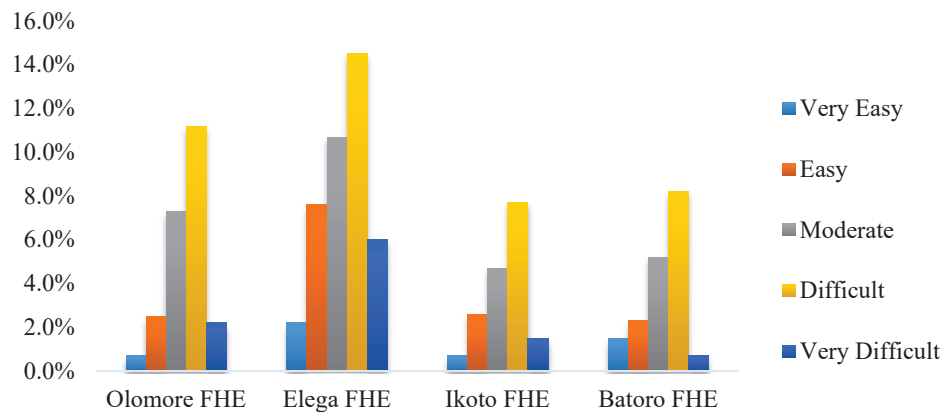


Fig. 3: Assessment of accessibility to federal housing units (Source: authors' fieldwork, 2025).

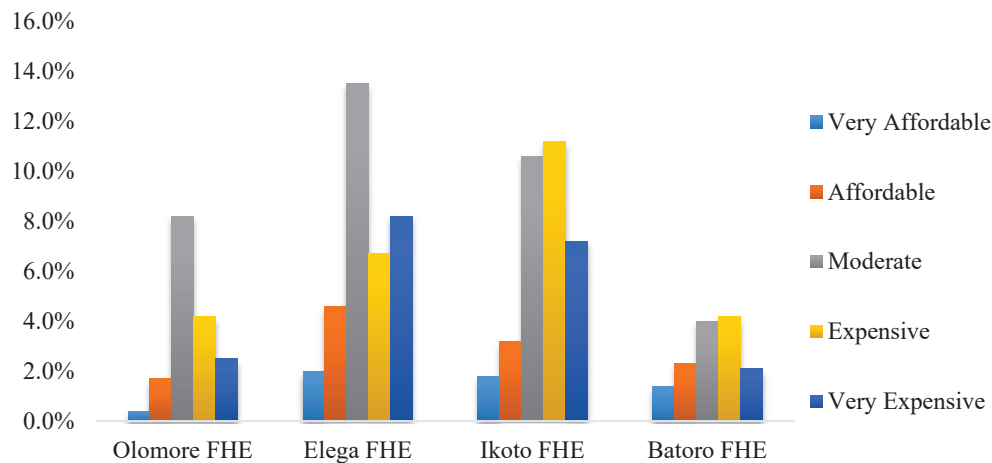


Fig. 4: Federal housing units' affordability level (Source: authors' fieldwork, 2025).

Assessment of accessibility to federal housing units

The process for publicising Federal housing units in Nigeria is carried out through the Federal Ministry of Works and Housing. A survey was conducted among the occupiers (residents) to assess the level of accessibility to Federal housing units. As revealed, 5.1% of the residents indicated that the accessibility to Federal housing units was straightforward, while 15% considered it easy. Most (41.6%) of the residents stated that Federal housing units were difficult to access, while 10.4% described it as difficult. Additionally, 27.9% described the accessibility to federal housing units as moderate (Fig. 3), but they emphasised that only the transfer of ownership is

moderately accessible, which is very expensive.

Level of affordability of federal housing units

The study examined the affordability of Federal housing units. As it was revealed, the majority of the residents (47.5%) believed that the housing units were expensive. Additionally, 22.5% stated that the cost is very expensive, while 6.5% considered the cost to be moderate. On the other hand, 17.2% and 6.3% claimed that the cost of obtaining a housing unit is cheap (affordable) and very affordable, respectively (Fig. 4). This indicates that the level of housing affordability is relatively high. However, the influence of speculators in the Federal housing delivery process

Table 3: AMSs of the housing financial burden

The residents' cost incurred	No Financial Burden		Less Financial Burden		Fair Financial Burden		Financial Burden		Huge Financial Burden		AMS	Rank
	No.	%	No.	%	No.	%	No.	%	No.	%		
Housing cost	2	1.5	8	6.0	11	8.2	46	34.3	67	50.0	4.25	2
Water Provision	3	2.2	7	5.2	10	7.5	50	37.3	64	47.8	4.23	3
Power Supply	1	0.7	4	3.0	6	4.5	43	32.1	80	59.7	4.47	1
Security Service	11	8.2	17	12.7	21	15.7	56	41.8	29	21.6	3.56	6
Transport to the place of work	1	0.7	12	9.0	13	9.7	52	38.8	56	41.8	4.12	4
Waste disposal	13	9.7	19	14.2	16	11.9	49	36.6	37	27.6	3.58	5

Source: authors' fieldwork, 2025

is significant and cannot be overlooked. Therefore, the Federal government should make the application process more accessible to the general public.

Housing financial burden on the residents

The financial burden associated with housing was assessed through Aggregated Mean Scores (AMSs) and analysed using the Pearson Product-Moment Correlation Coefficient (r). This analysis aimed to understand how land costs, house rents, and additional expenses contribute to the financial challenges the residents (occupiers) face. Data collected were evaluated on a five-point scale:

- (1) for "no financial burden,"
- (2) for "less financial burden,"
- (3) for "fair financial burden,"
- (4) for "financial burden,"
- (5) for "huge financial burden."

As the study revealed, Table 3 presents residents' perceptions regarding housing costs and other expenses that contribute to their financial burden. These cost variables were ranked based on their AMSs. Notably, the electricity cost ranked as the residents' highest financial burden, with an AMS of 4.47. In contrast, the cost associated with security services received the lowest ranking, with an AMS of 3.56. Housing costs ranked second with an AMS of 4.25, followed by water provision in third place with an AMS of 4.23. The cost of transportation to the workplace came in fourth, with an AMS of 4.12, and waste disposal ranked fifth with an AMS of 3.58 (Table 3). These findings indicate that all these costs contribute to the financial burden experienced by the residents (occupiers of the Federal housing units).

These findings indicate that residents (occupiers) of the Federal housing estates in Ogun State are

facing significant financial burdens related to housing. This aligns with the research conducted by [Fakere et al., \(2018\)](#), [Morakinyo et al., \(2014\)](#), and [Mohit & Nazyddah \(2011\)](#), which found that occupiers of public housing often incur additional costs for basic facilities and utilities, relative to their income levels. Physical observations also showed that many infrastructural facilities in the Federal housing estates, such as roads and drainage systems, were in disrepair. In many instances, the residents (occupiers) could not provide essential services, such as water supply, with limited resources. Further analysis using the Pearson Product-Moment Correlation Coefficient (r) revealed significant relationships between housing costs and other expenses incurred by the residents. As shown in Table 4, there were significant correlations ($p < 0.05$) between the housing cost and the following fees: water provision ($p = 0.001$), power supply ($p = 0.001$), and transportation to work ($p = 0.006$). However, no significant relationships were found ($p > 0.05$) between the cost of housing and expenses for security services ($p = 0.215$) and waste disposal ($p = 0.083$). Additionally, there are important connections between certain costs incurred by residents. For example, there is a notable relationship between power supply costs and water provision (as shown in Table 4). However, some inconsistencies exist in the relationships between different costs incurred by the residents (Table 4). This suggests that the residents (occupiers of the Federal housing units) face a significant financial burden related to housing. Therefore, the FMWH should prioritise providing water and power alongside housing development efforts.

This contradicts the widely accepted benchmark that housing should not consume more than 30% of

Table 4: Relationship between housing cost and other costs incurred

Residents' costs incurred on:		Housing Cost	Water Provision	Power Supply	Security Service	Transport to the Place of Work	Waste Disposal
Housing Cost	Pearson Correlation	1	.994**	.992**	.671	.970**	.828
	Sig. (2-tailed)		.001	.001	.215	.006	.083
	Sum of Squares and Cross-products	14840.800	14570.800	17831.800	6153.800	12776.800	6781.800
	Covariance	3710.200	3642.700	4457.950	1538.450	3194.200	1695.450
	N	5	5	5	5	5	5
Water Provision	Pearson Correlation	.994**	1	.976**	.741	.986**	.880*
	Sig. (2-tailed)	.001		.004	.152	.002	.049
	Sum of Squares and Cross-products	14570.800	14486.800	17338.800	6714.800	12829.800	7118.800
	Covariance	3642.700	3621.700	4334.700	1678.700	3207.450	1779.700
	N	5	5	5	5	5	5
Power Supply	Pearson Correlation	.992**	.976**	1	.577	.932*	.760
	Sig. (2-tailed)	.001	.004		.308	.021	.136
	Sum of Squares and Cross-products	17831.800	17338.800	21782.800	6416.800	14876.800	7542.800
	Covariance	4457.950	4334.700	5445.700	1604.200	3719.200	1885.700
	N	5	5	5	5	5	5
Security Service	Pearson Correlation	.671	.741	.577	1	.827	.959**
	Sig. (2-tailed)	.215	.152	.308		.084	.010
	Sum of Squares and Cross-products	6153.800	6714.800	6416.800	5672.800	6737.800	4856.800
	Covariance	1538.450	1678.700	1604.200	1418.200	1684.450	1214.200
	N	5	5	5	5	5	5
Transport to the Place of Work	Pearson Correlation	.970**	.986**	.932*	.827	1	.935*
	Sig. (2-tailed)	.006	.002	.021	.084		.020
	Sum of Squares and Cross-products	12776.800	12829.800	14876.800	6737.800	11694.800	6798.800
	Covariance	3194.200	3207.450	3719.200	1684.450	2923.700	1699.700
	N	5	5	5	5	5	5
Waste Disposal	Pearson Correlation	.828	.880*	.760	.959**	.935*	1
	Sig. (2-tailed)	.083	.049	.136	.010	.020	
	Sum of Squares and Cross-products	6781.800	7118.800	7542.800	4856.800	6798.800	4518.800
	Covariance	1695.450	1779.700	1885.700	1214.200	1699.700	1129.700
	N	5	5	5	5	5	5

** . Correlation is significant at the 0.01 level (2-tailed).

* . Correlation is significant at the 0.05 level (2-tailed).

Source: Authors' fieldwork, 2025.

household income; exceeding this threshold indicates a housing cost burden, while above 50% is considered severe (Stone, 2006; UN-Habitat, 2011). Hence, it suggests that many residents (occupants of federal housing units in Nigeria) face significant financial strain despite the «affordable» label attached to these housing units. It shows that the Federal government housing programs underestimate the earning power of intended beneficiaries. For instance, many urban dwellers who operate in the informal sector with irregular incomes will find it difficult to meet monthly or down payments for government-subsidised housing units. Even with instalment plans

or mortgage arrangements, the repayment terms are unaffordable (Makinde, 2014; Ibem & Azuh, 2011; Olotuah, 2010).

Assessment of the housing environment

The physical condition of the housing environment is essential for ensuring safety, comfort, health, aesthetics, and positive interactions among residents (Irouke, 2017; Jiboye, 2010). This prompted an assessment of the physical conditions of the Federal Housing Estates in Ogun State, Nigeria. A survey was conducted to gather the residents' opinions regarding their housing environment (Fig. 5). The

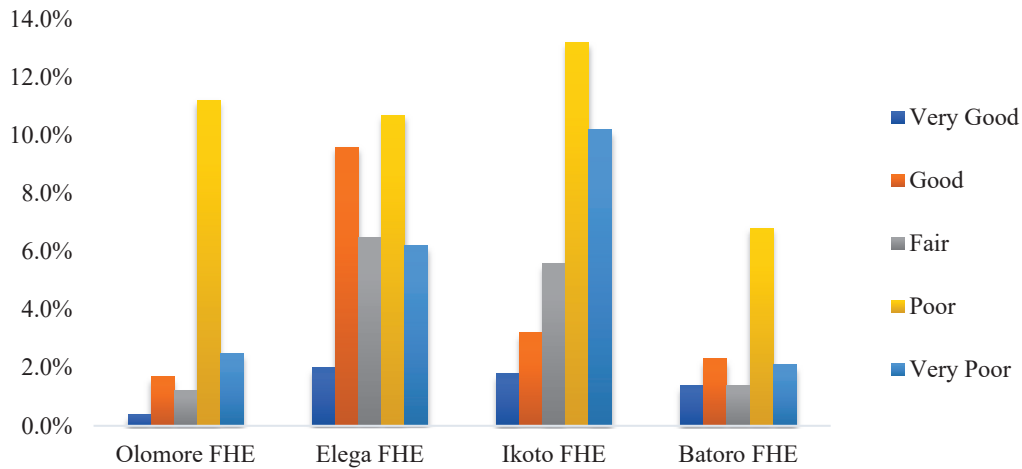


Fig. 5: Assessment of the housing environment (Source: authors' fieldwork, 2025).

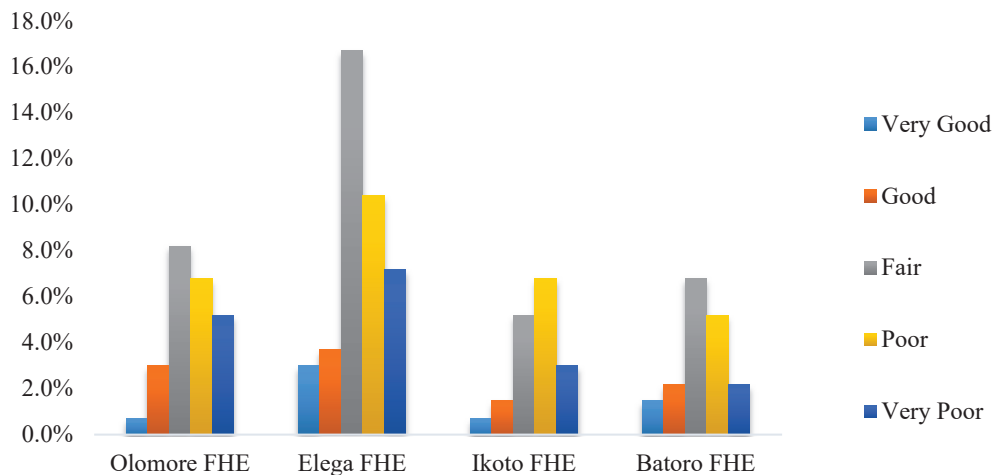


Fig. 6: Condition of roads in the federal housing estates (Source: authors' fieldwork, 2025).

results showed that 12% of the residents rated the physical condition of their housing environment as very good, and 31.6% considered it good. Meanwhile, 13.5% of respondents were indifferent about their housing conditions. In contrast, a majority of 38.5% reported that the housing environment is poor, and 4.5% rated it as very poor. Therefore, the Federal government should enhance its efforts to improve the housing environment, as this would significantly benefit the well-being of the residents.

Also, in assessing the housing environment, roads were evaluated as a fundamental requirement for housing development (facilitating public interactions

and conveniently connecting various human activities). The assessment was conducted on the condition of the roads in the Federal housing estates. According to the findings illustrated in Fig. 6, most (36.9%) residents rated the housing estates' roads fairly. Meanwhile, 5.9% rated them as very good, and 10.4% as good. However, 29.2% of the residents reported that the housing estates' roads were poor, while 17.6% described the streets as very poor. These results indicate that the Federal government needs to repair and maintain road infrastructure within these housing estates to prevent the situation from worsening.

CONCLUSION

This study critically examined the effectiveness of government-funded housing delivery through the lens of public awareness, accessibility, and affordability. The findings demonstrated that while many residents were aware of Federal housing initiatives, significant challenges persist in inequitable access and affordability. The data revealed that over half of the residents found the housing units difficult to access, nearly 70% considered them unaffordable, and a majority bore a disproportionate financial burden due to inadequate infrastructure and essential services. The study also found that many housing estates suffer from poor environmental conditions and infrastructural neglect, undermining the quality and sustainability of government housing investments. The implications are clear: public housing delivery mechanisms fail to meet their intended social outcomes. The presence of communication gaps, speculative ownership transfers, and insufficient infrastructural provisioning points to structural deficiencies in the policy design and implementation process. Addressing these failures requires a shift from episodic interventions to a more integrated, systemic, and people-centred approach. Affordable housing should not only be about physical units but also about holistic residential environments that promote well-being, reduce inequality, and enable economic productivity. The Federal government must, therefore, reaffirm its commitment to housing as a fundamental social good by ensuring transparency, inclusivity, and adequate resource allocation across all levels of policy execution. To address the issues highlighted, the study recommends:

a. Rehabilitation of Federal Housing Estates: Immediate renovation of ageing estates, particularly focusing on road networks and structural integrity, to restore safety and habitability.

b. Enhanced Public Awareness Campaigns: Strengthen the dissemination of information regarding housing programmes to ensure equal opportunity and reduce speculative bottlenecks in housing access.

c. Provision of Basic Infrastructure: Integrate essential services—especially water and power supply—into housing delivery to reduce residents' living costs and enhance long-term sustainability.

d. Sustained Political Commitment: Demonstrate political will through increased public funding,

implementation of pro-poor housing subsidies, and inter-ministerial coordination to scale up access to affordable, decent housing for all.

AUTHOR CONTRIBUTIONS

O. F. Jokotade conceptualized the study, designed the research framework, and authored the original draft. A. G. Olabisi co-developed the methodology and conducted the formal data analysis. A.S. Dolapo supervised the research and contributed to the field investigation alongside O. O. Abdulgafar. Data curation was carried out by O. O. Phillips and A. O. Abiodun. F. A. Akintunde critically reviewed and edited the manuscript for clarity, coherence, and academic rigour. All authors reviewed and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, they have witnessed all ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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ABBREVIATIONS (NOMENCLATURE)

r	Pearson product-moment correlation coefficient
AMS	Aggregated mean scores
FHE	Federal Housing Estates
FMWH	Federal Ministry of Works and Housing
GIS	Geographic Information System
HAI	Housing Affordability Index
NBRI	Nigeria Building and Road Research Institute
PIR	Price-to-Income Ratio

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ORIGINAL RESEARCH PAPER

Prediction of land use changes in Hyrcanian forests using an Artificial Neural Network model

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ABSTRACT

BACKGROUND AND OBJECTIVES: Land use change is a pressing global environmental crisis requiring scientific study for sustainable regional decisions. This study analyzes the spatial-temporal dynamics of land use in the Hyrcanian forests of western Mazandaran province from 2013-2023 using remote sensing data. Image classification was based on six land use classes: vegetation, built-up, agriculture, water bodies, forest, and bare land.

METHODS: An Artificial Neural Network was employed to predict land use changes over ten years. The model was validated by comparing the simulated 2023 map with the actual map, resulting in a Kappa coefficient of 92%.

FINDINGS: Land use change maps from 2013-2023 show that built-up areas increased by 26.5517 km², while forest and other vegetation decreased by 43.6353 km² and 85.1967 km², respectively. Projections for 2023-2033 indicate similar trends: an increase in built-up areas by 31.3106 km² and a decrease in forest and other natural areas by 8.875 km² and 16.6104 km², respectively.

CONCLUSION: This research offers a valuable tool for the sustainable management of Hyrcanian forests, aiding informed decision-making for environmental improvement, identifying threats, optimal resource management, and predicting the effects of climate change. It offers valuable insights for sustainable planning, management, and improved environmental outcomes.

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INTRODUCTION

In recent years, rapid economic development and urban sprawl, often driven by the conversion of large amounts of agricultural land to construction and other types of urban land, have significantly altered regional land use patterns and natural landscapes, and have compromised the health of terrestrial and aquatic environments (Luo *et al.*, 2020). This is particularly evident in the vicinity of urban areas (Munksgaard *et al.*, 2019). Land use change is one of the environmental hazards and ecological crises that humanity faces today. Land use is a term used to describe human use of land that results in changes in the natural characteristics of an area, including vegetation, water resources, soil, rocks, and other natural resources. (EPA, 2024). In response to rapid population growth, industrial activities, development, and urbanization have also grown rapidly, and the negative result of this growth is the serious water crisis and its pollution in today's world, which leads to various diseases and threatens human health. Understanding the extent of the adverse effects of human activities on ecosystems can help humanity comprehend the impact of ecosystem health on the human living environment, which is reflected in social, population, and economic responses (Costanza *et al.*, 2014). Land use patterns reflect the interaction between human activities and the natural environment. Land use change, which is often influenced by policies, is the result of a complex interaction between social-ecological feedbacks and socio-economic developments (Wang *et al.*, 2022). Land use change refers to temporal changes in the form and type of land use that are driven by social and economic changes (Zhang and Li, 2022a). Land use morphology represents the quantity and spatial structure of land use in a specific area over a given period of time. Improving land use morphology leads to sustainable use of land resources. In the current context, the conversion of natural areas to developed or agricultural areas is considered to be one of the major factors driving significant changes in land use, especially in developing countries (Baig *et al.*, 2022). Socioeconomic changes, including population growth, increasing globalization, urbanization, changes in supply, demand, and trade patterns, technological advances, dietary habits, or public opinion, are considered to be major factors in land use changes and agricultural practices (Beyer *et al.*,

2022; Subedi *et al.*, 2022). According to the Food and Agriculture Organization (FAO), agricultural development is responsible for about 90% of global deforestation (DeValue *et al.*, 2022). More than half of global forest loss occurs due to conversion to agricultural land. Deforestation in developing countries, such as Iran, is mainly due to the expansion of cultivated land and the production of charcoal and timber. The intensification and expansion of agriculture around the world have placed significant pressure on the environment and climate, threatening the health, security, and survival of people and the planet (EEA, 2021). However, land use changes cannot usually be attributed to a single factor, but are the result of a complex interaction of climate, politics, and socio-economic conditions (Ustaoglu and Williams, 2017). In addition to significant impacts on our planet's current and future climate (Tattoni *et al.*, 2017), these changes have major implications for biodiversity (Powers and Jetz, 2019) and human well-being through changes in key ecosystem services (Gomes *et al.*, 2021). Given that land use change is the main driver of environmental change (Islami *et al.*, 2022) and the main challenge is to preserve the environment while increasing economic and social benefits, understanding the patterns and trends of land use change at different scales is of great importance (Salehi *et al.*, 2018). Knowing the ratio of land uses and how they change over time is one of the most important issues in management planning. Command and control in land use also refers to a set of activities and processes used to manage and monitor land use, which requires an accurate and timely prediction of future land use changes. Geographic Information Systems (GIS) and Remote Sensing (RS) have been key tools for identifying and monitoring land use changes for many years. Landsat satellite images, especially at large scales, play an important role in classifying different land use types (Zhang & Li, 2022b). Access to multi-temporal remotely sensed data is essential for examining past changes and analyzing land use trends. QGIS is an efficient tool for quantifying these changes. In recent years, various methods such as supervised classification, unsupervised classification, Principal Component Analysis (PCA), neural networks, and fuzzy classification have been developed to identify land use changes using remote sensing data (Butt *et al.*, 2015). Also, in the past two decades, regression

methods have been widely used for modeling land use predictions (Huu *et al.*, 2022). In the past half-century, the watersheds of the Hyrcanian forests of Mazandaran province have faced serious threats from land use change, including clearing forests for agricultural development and expansion of construction due to increasing land values. Analyzing and monitoring land use changes is of great importance for understanding the depth and extent of these changes, as well as for integrated watershed management (Malede *et al.*, 2023). The most important problem of these ecosystems is the lack of compliance with carrying capacity, meaning the imbalance between existing resources and the amount and manner in which humans use them. The carrying capacity of resources is defined as the size of the population that can be maintained by using local resources and other natural resources, intelligence, technology and other conditions to ensure a material standard of living in accordance with local socio-cultural norms in a predictable period (Wang *et al.*, 2018; Sun *et al.*, 2020). The most obvious feature of this type of imbalance is the reduction of environmental quality and also the reduction of quality of life. Therefore, finding a solution to maintain the integrity of the interaction between environmental protection and development has become an important practical concern for planners. In recent years, numerous studies have been conducted at home and abroad in the field of analyzing land use changes in different watersheds. Karimzadeh Motlagh *et al.*, (2022) conducted a study to assess and predict land use changes using the Markov_CA model in the Zayandeh Rood River Basin. They examined the rate of land use changes from 1996 to 2018 and then predicted future changes for the years 2030 and 2050. Also, Jahdi (2023) conducted a study on modeling land use changes and future predictions using ANN-CA simulation in the 25th watershed of Shenrud Siahkal in Gilan Province. She evaluated land use changes over a 21-year period from 2001 to 2022. She also used modeling to predict the amount of increase in man-made areas and the decrease in forests and other natural areas in the next 21 years. Schirpke *et al.* (2023) assessed the past and future impacts of land use change on ecosystem services in Austria. Their findings showed that socio-economic drivers had the greatest impact on land use change in the past. Atef *et al.* (2024) conducted a

simulation study of future land use cover changes in the Al-Fayoum Governorate, Greece, using satellite data and a CA-Markov model. They used the IDRISI-TerrSet software and found that the modeled future scenarios in LULC indicate a significant change in LULC classes over time, especially for the year 2030. Using Land-N2N, an effective and efficient model for simulating demand-driven changes in mixed-use lands, Gao *et al.* (2025) investigated the CLUMondo model through four strategies, resulting in an improved version called "Land-N2N." They stated that the Land-N2N model has the ability to provide scientific solutions for land management by predicting land changes. The aim of this research is to model land use changes and predict the future using Artificial Neural Network (ANN) technique in the western basin of Hyrcanian forests for optimal and sustainable development in 2024. Modeling temporal and spatial changes in land use is important for investigating the dynamic processes of land use in the western basin of Mazandaran province, which is the hub of Iranian tourism. The identification of driving forces is done by utilizing a combination of remote sensing and geographic information systems in the preparation of land use maps and physical, social, and economic data. Physical and socio-economic factors were identified as potential drivers of land use changes. Land use class changes are analyzed using Landsat satellite images in 2003, 2013, and 2023. Also, the prediction of land use changes in the next ten years in the study area is studied using an ANN. Finally, suggestions for management measures for sustainable use and land use management in the future, such as managing the development process and protecting the valuable Hyrcanian forests, are presented.

MATERIALS AND METHODS

Study area

The western region of Mazandaran, which, in addition to being homogeneous, has undergone many changes in the landscape due to being the most tourist-friendly part of this basin, was selected as the study area. This region includes the cities of Ramsar, Tonekabon, and Abbasabad, which are selected based on the sub-basins corresponding to the country or political-administrative divisions of the selected cities. The area of this region is 2887.79 square kilometers. Fig. 1 shows the study

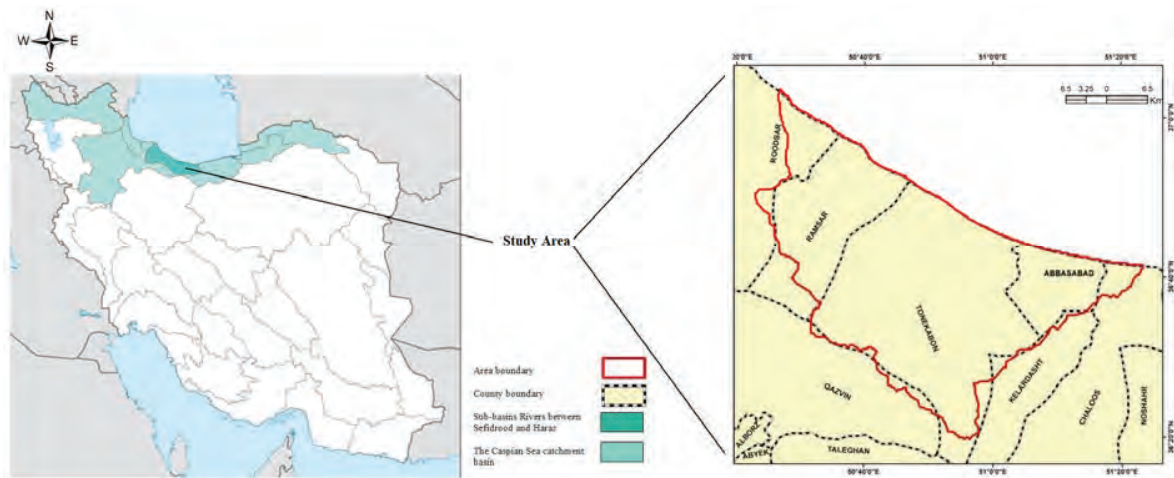


Fig. 1: Location of the study area, including the watershed, sub-watershed, and counties (Source: Authors)

area. These areas are hot and humid in summer and temperate in winter. Also, due to their proximity to the Caspian Sea, the Alborz Mountain wall, and the short distance between the mountains and the sea, they have moderate temperatures and high humidity, so that the annual rainfall reaches 1300 mm, and the seasonal distribution of rain is proportional and the dry period is very short (Mazandaran Province Natural Resources and Watershed Management Department, 2023).

Research method

In order to investigate land use changes, according to the country's official population censuses and also the latest Landsat satellite images, ten-year time nodes, i.e., 2003, 2013, and 2023, were selected to select the relevant satellite images. For this purpose, all satellite images in this study were used from the US Geological Survey website (<http://earthexplorer.usgs.gov/>) and Landsat 5 and 9 images from Collection 2 and Level 1 with a resolution of 30x30. Table 1 shows the characteristics of the satellite images used in this study.

Considering the division of land cover into six categories, including Bare-land, Forest, Rice, Build-up, Vegetation, and Water body (Table 2), based on the biological cycle of rice growth (after planting and before harvesting) and cloud cover, the best time to select images was during the summer period. As a problem, due to the humid subtropical climate, images without clouds or with cloud cover less than

10% were not available on a specific date. Therefore, images with cloud cover less than 10% from July 15 to August 15 were selected and downloaded.

Considering the necessity of pre-processing for analyzing satellite images to increase the visual interpretation and spectral resolution of the earth's surface features (Seyam *et al.*, 2023), the pre-processing of the downloaded images includes image integration, atmospheric corrections to remove and correct the atmospheric effects caused by the presence of gases, solid and liquid particles from the atmosphere, and geometric corrections using ENVI version 5.6 software with the classification method for tree images. It was done in 2003, 2013, and 2023. Although the current modeling framework primarily relies on remotely sensed data and land cover maps (2003, 2013, 2023) to simulate and predict land use dynamics, it is important to acknowledge that land use change is also strongly influenced by socio-economic factors. Variables such as population growth, accessibility to transportation networks, spatial planning policies, and local economic drivers can provide additional explanatory power for predictive models. Due to the limited availability of spatially explicit socio-economic datasets at the required resolution, these variables were not incorporated in the present analysis. However, the adopted ANN framework is flexible and can integrate such variables in future studies to further enhance prediction accuracy and better capture human-environment interactions.

Table 1: Characteristics of satellite images used in this study

Satellite	Sensor	Acquisition Date	Bands used	Spatial Resolution	Processing
Landsat 5	Thematic Mapper (TM)	2003	B1, B2, B3, B4, B5, B7	30 m	collection 2-level 1
Landsat 5	Thematic Mapper (TM)	2013	B1, B2, B3, B4, B5, B7	30 m	collection 2-level 1
Landsat 9	Thematic Mapper (TM)	2023	B2, B3, B4, B5, B6, B7	30 m	collection 2-level 1

Table 2: Land cover/use classification characteristics of this study

LU/LC category	LU/LC description
Bare-land	Areas covered by exposed soil and rocks, sandy soil, and beaches) and devoid of built-up structure and vegetation or plants.
Build-up	Areas covered by settlements (urban and rural areas), roads, commercial or industrial structures, and buildings.
Forest	Areas covered by trees.
Rice	Agricultural areas producing rice.
Vegetation	Areas covered by grass, tea garden, bush and shrub, and cropland.
Water body	Areas covered by river, wetland, dam water, seawater, fish breeding pond, Farm ponds and irrigation reservoirs for agriculture (especially for rice).

Analytical framework

In the present study, the initial analytical framework focused on quantifying land-use changes between 2003, 2013, and 2023 by comparing classified land-use maps of the western Hyrcanian forests (Ramsar, Tonekabon, and Abbasabad). The Artificial Neural Network (ANN) model in the MOLUSCE plugin of QGIS was used to simulate and project future land-use dynamics based on these time series data. For each pair of time points, the spatial relationship between input maps was examined, and a transition matrix was generated to feed the predictive model. The model was then validated by comparing the simulated 2023 map with the observed 2023 land-use map, yielding a Kappa coefficient of 92%.

Model validation metrics

Although the Kappa coefficient demonstrates a high level of agreement, additional accuracy measures were also considered. The Overall classification Accuracy (OA) reached 94%, while the mean Producer's Accuracy (PA) and User's Accuracy (UA) across all land-use classes were approximately 91% and 90%, respectively. A detailed confusion matrix was also generated to assess class-specific misclassifications, ensuring that no single class disproportionately influenced the overall performance. These complementary metrics further confirm the robustness of the ANN-based

prediction framework. Beyond reporting changes in total area (km²) for each land-use class, a simple spatial-ecological assessment was also conducted to better capture the patterns of landscape transformation. Specifically, the Forest Fragmentation Index (FFI)—defined as the number of discrete forest patches per 100 km²—increased from 3.2 in 2013 to 4.7 in 2023, indicating a more fragmented forest structure. Likewise, the Connectivity Index (CI)—the percentage of forest patches located within 100 m of each other—declined from 68% in 2013 to 55% in 2023, suggesting that the remaining forest areas became more isolated over time. These additional spatial metrics highlight that land-use changes in the region are not only reducing forest extent but also disrupting ecosystem connectivity and habitat integrity, which are critical considerations for sustainable management.

RESULTS AND DISCUSSION

Investigating land use changes in Hyrcanian forests and predicting the trend of these changes has several benefits, which in summary are:

- *Identify threats:* By examining land use changes, it is possible to identify patterns of degradation and major threats. For example, the uncontrolled expansion of man-made, agricultural, or industrial areas on the edge of the forest can lead to habitat destruction, increased pollution, and reduced

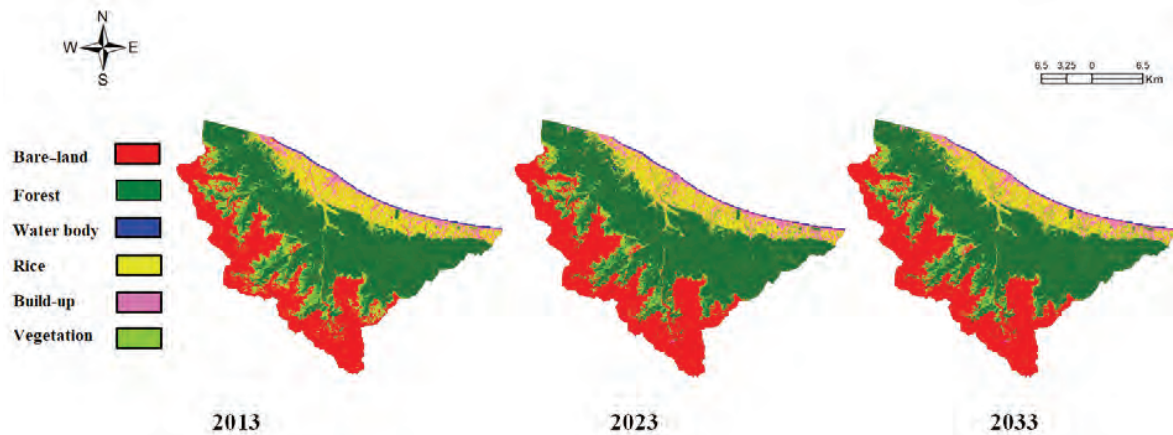


Fig. 2: Map of temporal-spatial changes in land use classes (Source: Authors)

biodiversity.

- *Optimal resource management:* With accurate information on the status of vegetation and land use, better management plans can be developed to preserve and restore forests. These plans can include designating protected areas, implement afforestation projects, and control human activities.

- *Predicting the impacts of climate change:* Land use changes can exacerbate the impacts of climate change. By modeling and predicting the course of change, we can assess potential impacts and plan for their mitigation. For example, converting forests to agricultural land can increase greenhouse gas emissions and reduce the forest's ability to absorb carbon.

- *Economic and social assessment:* Land use changes can have significant impacts on local economies and communities. By examining these impacts, policies can be adopted that both help conserve forests and benefit local communities. For example, developing sustainable tourism can provide an alternative source of income for local communities and reduce their dependence on forest resources.

- *Informed decision-making:* With accurate information and reliable predictions, decision-makers can adopt policies and programs that help maintain the ecological integrity of the Hyrcanian forests. This information can be effective in allocating funds, setting research priorities, and implementing conservation projects.

Fig. 2 shows a map of the temporal-spatial changes in the western region of Mazandaran province in

the six land use classes explained in the previous section, for the years 2013, 2023, and the forecast for 2033, respectively. While the main projections shown in Fig. 2 follow a business-as-usual pathway, additional scenario analyses were performed to explore potential alternatives. In a conservation intervention scenario, where stricter land-use controls and afforestation programs are assumed, the projected loss of forest cover from 2023 to 2033 would be reduced from 8.9 km² to approximately 4.0 km², and the expansion of built-up areas would slow from 31.3 km² to 20.0 km². Conversely, in a policy-driven urban expansion scenario, where fewer restrictions on construction are assumed, built-up areas could increase by as much as 40.0 km², with a corresponding forest loss of around 12.0 km². These exploratory scenarios highlight that land-use dynamics are not strictly deterministic and can vary significantly depending on management strategies and policy directions.

To better understand Fig. 2 and analyze the changes in the six land use classes in three-time nodes, Table 3 is presented. Based on this table, the rate of change in the classes between 2013 and 2023 can be calculated, and the changes in 2033 can be predicted.

Based on the data in Table 3, significant changes can be observed in the land cover of the western basin of Mazandaran from 2013 to 2023 and the predictions for 2033. From 2013 to 2023, respectively, bare land increased by 54.1539 km², water bodies by 3.9176 km², man-made land by 26.5517 km²,

Table 3: Changes in land use classes at three time points (Source: Authors)

Classes	Area (km ²)		
	2013	2023	2033
Bare-land	742.5288	796.6827	795.689
Forest	1391.1453	1347.51	1338.635
Water body	20.9709	24.8885	26.665
Rice	286.0263	304.2354	315.3519
Build-up	135.4917	162.0434	193.354
Vegetation	296.8993	211.7026	195.0922

and agricultural land by 18.2091 km², while forests decreased by 43.6353 km² and vegetation by 85.1967 km². The projections also show that from 2023 to 2033, the trend of changes will be somewhat moderated. Thus, bare land will decrease by 0.9937 km², forest by 8.875 km², and vegetation by 16.6104 km². It is also expected that agricultural land, which is mostly rice in this region, will increase by 11.1165 km², water bodies by 1.7765 km², and man-made land by 31.3106 km². The projected slight decrease in barren land between 2023 and 2033 should not be taken as a sign of improvement. This change is very small and cannot compensate for the losses caused by past degradation. The continuous increase in man-made land reflects urban, industrial, and infrastructure development in the region and will continue to be an important factor in land cover changes in the region. Urbanization and industrial development lead to increased production of urban and industrial waste and wastewater. Failure to properly treat these wastewaters can cause pollution of water and soil resources. The increasing trend of rice planting also indicates increased market demand, farmers' interest in cultivating this crop, and the consolidation of Mazandaran's position as the country's rice production hub. The conversion of natural lands to agriculture is usually accompanied by increased use of fertilizers and pesticides. These substances enter the soil and groundwater and cause pollution. The loss of forests and vegetation has been largely due to logging for commercial exploitation, agricultural development, and construction. In addition, climate change and drought have also contributed to the loss of vegetation in the region. This change leads to increased soil erosion, reduced biodiversity, increased flood risk, and reduced water resources. It should be noted that the increase in water bodies is not due to an increase in water resources, but rather due to the expansion of rice agricultural lands.

The loss of Hyrcanian forests not only destroys the habitat of unique plant and animal species, but also disrupts their vital function in regulating the water cycle, preventing soil erosion, and absorbing carbon dioxide. The reduction in vegetation also indicates the destruction of the region's orchards, pastures, and grasslands. These ecosystems play an important role in feeding livestock, conserving soil, and regulating water flow, and their destruction leads to increased runoff, soil erosion, and reduced land fertility. Reduced vegetation cover reduces the soil's ability to absorb water, leading to increased runoff and the risk of flooding. This can cause significant loss of life and property, especially in areas with high rainfall, such as Mazandaran. To prevent this trend from continuing, serious measures need to be taken to protect existing forests and rangelands, restore degraded forests, and promote sustainable agriculture.

CONCLUSION

Hyrcanian forests, with their ancient history and unique biodiversity, play a key role in the ecological sustainability of the region. In addition to providing a valuable genetic resource, these forests directly impact the quality of life of local communities and beyond by regulating climate cycles, protecting soil and reducing erosion, and sequestering carbon dioxide. Maintaining the ecological integrity of these forests requires a comprehensive approach that, in addition to sustainable resource management, pays special attention to reducing threats from land-use change, pollution, and invasive species. Continuous monitoring of ecosystem health, careful assessment of the ecological services provided, and active participation of stakeholders in the decision-making process are essential measures to ensure the long-term sustainability of this valuable natural heritage. Furthermore, the effective implementation of any land-use management strategy depends heavily on

the active involvement of local stakeholders, including community members, farmers, municipal authorities, and regional planners. In the context of the Hyrcanian forests, the perceptions, knowledge, and participation of local actors are crucial for designing practical and socially acceptable policies. Integrating stakeholder feedback can enhance policy relevance, improve compliance with conservation measures, and ensure that development plans align with local needs and values. Therefore, future management efforts and policy frameworks derived from this study should prioritize stakeholder engagement and participatory decision-making processes. Considering that this area is called the natural and green tourism hub of Iran and is the most touristic province in the country due to its short distance and proximity to the capital province, as well as its beautiful nature and diverse landscapes, its assessment in the region is essential. Investigating land use changes and predicting their trends is a powerful tool for sustainable management of Hyrcanian forests that helps identify threats, optimally manage resources, predict the effects of climate change, assess economic and social factors, and make informed decisions. Therefore, this study provides valuable findings that can play a role in future sustainable planning and management and help managers make informed decisions to improve the environment. The ANN model is an effective tool in predicting land use and cover by successfully simulating different land use classes in the western region of Mazandaran province, which includes the Hyrcanian forests. Therefore, the use of a fixed base of land use and cover maps is recommended for future studies in similar areas. Comparison of satellite images from different years shows that in the past these forests were denser and had a greater northern expansion, but due to population growth, agricultural development and increased exploitation, the forest area has decreased and its northern limit has been limited to the Alborz foothills. This study showed how the proposed ANN model can be used to better simulate complex and dynamic land use changes over time. Of all the changes, the most worrying situation in the region is the reduction of forest land and vegetation cover and the increase in built-up land. The destruction of forests and pastures reduces the capacity to absorb Carbon Dioxide (CO₂) and contributes to the intensification of climate change. Green covers are natural carbon sinks and

their destruction leads to the release of CO₂ into the atmosphere. Land use change can cause changes in the species composition of the region, and species that are more resistant to human conditions replace native and sensitive species. If current land use trends continue, it is predicted that by 2033, forest area will decrease by 8,875 km² and man-made land will increase by 31,3106 km², which will undoubtedly change other ecosystems in the region. It should be noted that the intensification of agricultural land use and urban expansion will primarily lead to a decrease in ecosystem services in the regions. Given the precious heritage of the Hyrcanian forests, which are remnants of the Tertiary geological period and date back to the Tertiary period, and the role of ecotourism in the socio-economic development of this region, it is essential to preserve the quality of its environment. In fact, ecotourism can act as an alternative source of income for local communities and reduce their dependence on forest resources. However, the development of ecotourism should be in a way that helps preserve the environment of the region. Therefore, management and planning of the study area are emphasized. According to previous studies, socio-economic factors such as economic growth, political systems and technological developments have played a major role in land use change in the past. This is also true for the Hyrcanian forests. The expansion of agriculture and the development of cities on the edges of forests, which are a result of economic growth and technological developments, have led to the destruction and conversion of part of these forests to agricultural and residential lands. Ineffective policies and lack of proper management of resources related to political systems have also played a role in the destruction of forests. To better manage this situation, the following strategies can be considered:

- *Protecting forest areas:* Designating protected areas and implementing conservation programs to prevent forest destruction
- *Controlling land use change:* Enforcing strict laws to control land use change and prevent the conversion of forests to urban and agricultural areas
- *Restoration of degraded areas:* Implementation of afforestation projects and restoration of degraded areas
- *Promotion of sustainable agriculture:* Promotion of sustainable agricultural methods that help

conserve soil and water and avoid the use of chemical fertilizers and pesticides.

- *Development of sustainable ecotourism:* Development of sustainable ecotourism that helps preserve the environment of the region and provides benefits to local communities.

- *Raising public awareness:* Raising public awareness about the importance of forests and the need to preserve them

- *Stakeholder participation:* Participation of local stakeholders in the decision-making and planning process

AUTHOR CONTRIBUTIONS

M. Jadidi designed the study, collected and analyzed the data, and drafted the manuscript. M. J. Amiri contributed to the data analysis and manuscript revision. All authors reviewed and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

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ABBREVIATIONS (NOMENCLATURE)

There are no abbreviations.

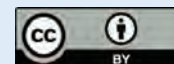
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ORIGINAL RESEARCH PAPER

Trends and trajectories in Human Resource Analytics: A scopus-based bibliometric study of knowledge domains and research evolution

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ABSTRACT

BACKGROUND AND OBJECTIVES: Human Resource Analytics has become a strategic enabler in modern workforce management, particularly amid digital transformation. However, scholarly research in Human Resource Analytics remains fragmented across regions and disciplines. This study employs bibliometric analysis to map global research output in Human Resource Analytics from 2012 to 2024, identifying trends, influential contributors, thematic concentrations, and underexplored areas.

METHODS: A bibliometric analysis approach was applied using data retrieved from the Scopus database. The dataset covered publication metadata, including authorship, institutional affiliation, geographic origin, keywords, sources, and citation counts. VOSviewer software was used to construct visual maps illustrating keyword co-occurrence, co-authorship networks, and citation clusters, enabling a comprehensive overview of research activity and intellectual structure in the Human Resource Analytics.

FINDINGS: A total of 211 publications are identified and analysed over 13 years, involving 602 contributors. The analysis highlights 2,674 citations, with an average of 12.67 citations per paper. The corresponding h-index and g-index are 24 and 47, respectively. The results reveal three research themes. They present an increasing global interest, with leading contributions from high-income countries. The three core themes are workforce analytics, Artificial Intelligence in Human Resource Management, and strategic decision-making. Notably, low representation from developing regions and limited use of advanced predictive analytics highlight critical research gaps.

CONCLUSION: This study provides a comprehensive quantitative overview of the evolution of Human Resource Analytics scholarship. It guides future research by identifying emerging priorities, regional disparities, and methodological developments, offering valuable insights for advancing data-driven human resource practices and fostering more strategic, evidence-based decision-making in HR management and policy development globally.

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INTRODUCTION

Human Resource Management (HRM) is an essential element of corporate success, overseeing several responsibilities like recruitment, staff development, performance management, and retention. Historically, HR choices were frequently grounded in intuition, experience, and qualitative evaluations (Achoui, 2009). In the contemporary data-driven business landscape, businesses are progressively depending on HRM analytics to facilitate informed, evidence-based decision-making. The transition from feeling to analytics signifies a substantial transformation in the management of HR services, enabling firms to utilize extensive data to enhance labour efficiency, employee engagement, and overall organizational performance. HRM analytics, also known as people analytics or workforce analytics, entails the utilization of data analytical methodologies on HR data to identify patterns, forecast future trends, and enhance HR procedures. This enables HR departments to shift from a reactive to a proactive stance, thereby supporting the strategic objectives of the firm (Almonawer et al., 2023). The increasing reliance on HRM analytics is not only a response to the availability of data but also a necessity driven by the complexities of modern workforce dynamics (Arora et al., 2021). Organizations now face challenges such as managing remote and hybrid workforces, enhancing employee well-being, promoting diversity and inclusion, and addressing skill gaps in a rapidly changing digital economy (Ahmed et al., 2022; Ying et al., 2023). As organizations adopt more sophisticated HR technologies, such as machine learning algorithms and Artificial Intelligence (AI) powered tools, HRM analytics has evolved from simple descriptive reporting to more advanced techniques like predictive and prescriptive analytics (Islam et al., 2022). The use of AI in HRM analytics is particularly promising, offering potential solutions for automating repetitive HR tasks, reducing bias in recruitment, and enhancing employee engagement through personalized learning and development plans (Arora et al., 2023; Al-Hunaiyyan et al., 2021). Moreover, while HRM analytics has been widely adopted in large, data-rich organizations, smaller businesses and public sector institutions may face barriers such as limited data availability, lack of expertise, or resource constraints that prevent them from fully utilizing analytics tools. Understanding these disparities in

HRM analytics adoption can offer valuable insights into how best to democratize the benefits of analytics across different organizational contexts. However, as the field continues to grow, it remains imperative to critically examine the existing literature and map out the intellectual structure of HRM analytics research. There is a need to better understand which areas of HRM are most influenced by analytics, what methodologies are commonly employed, and where the gaps in the literature may exist (Huang et al., 2023). This type of analysis is also fundamental for identifying which technologies and innovations are driving the field forward and which aspects of HR are lagging in analytics adoption. A bibliometric approach not only highlights the most influential publications, authors, and research institutions in the field but also demonstrates citation patterns and intellectual collaborations, offering a clearer picture of how knowledge in HRM analytics is being generated and disseminated. This can also pinpoint which research topics are gaining momentum, which methodologies are favored, and where there might be opportunities for future exploration. The increasing significance of HRM analytics has sparked growing academic interest, resulting in a rapidly expanding body of research across a wide range of topics. Scholars have explored areas such as employee performance prediction, talent acquisition analytics, turnover prediction, and the use of AI in HR processes. Despite the increasing interest in HRM analytics, the academic literature remains fragmented and lacks a unified theoretical or methodological foundation. Studies often vary widely in scope, focus, and research design. For instance, while some scholars concentrate on the predictive capabilities of analytics in employee turnover or recruitment (Minbaeva, 2018; Marler & Boudreau, 2017), others explore its strategic impact on organizational performance (Arora et al., 2021). However, few studies offer comparative analyses across industries, organizational sizes, or geographic regions, which limits the generalizability of findings (Van den Heuvel & Bondarouk, 2017). Moreover, a substantial proportion of existing research is concentrated in Western contexts, particularly in North America and Europe, with limited attention paid to emerging economies or public sector organizations (Álvarez-Gutiérrez et al., 2022). This geographic bias restricts our understanding of how HRA functions under different cultural, regulatory,

and technological conditions. Additionally, many studies rely on qualitative or case-based approaches without leveraging longitudinal or big data analytics, highlighting a methodological gap in empirical rigor (Dahlbom *et al.*, 2020). Furthermore, there is a lack of clarity regarding the adoption challenges faced by Small and Medium-Sized Enterprises (SMEs), which often lack the infrastructure, data maturity, or expertise required to implement advanced Human Resource Analytics (HRA) tools (Huang *et al.*, 2023). Few studies systematically explore the barriers and enablers of analytics adoption beyond large corporations, leaving a significant portion of the organizational landscape underexplored. This study addresses these gaps by conducting a bibliometric analysis of HRA literature from 2012 to 2024 that underscores the need for a comprehensive bibliometric and systematic analysis to synthesize fragmented insights. This includes identifying dominant themes, leading contributors, and future directions, with a focus on revealing underexplored areas and methodological disparities that warrant scholarly attention. This paper aims to provide a comprehensive examination of HRM analytics literature. An in-depth overview of the field of HRM analytics is provided through the analysis of the most relevant academic publications, which is achieved through a systematic literature review and bibliometric analysis. Consequently, the primary objectives of this investigation are as follows:

- *To conduct a systematic literature review of the key research areas, methodologies, and themes in the field of HRA.*
- *To examine the publication trends in the field of human resource analytics.*
- *To determine the most productive authors in the field of HRA.*
- *To classify the most productive institutions in the field of HRA.*
- *To identify the most active countries in the field of HRA.*
- *To examine the most highly cited documents in the field of HRA.*

Literature review

Conceptual foundation of HRA

This study conducted a critical review to examine recent literature regarding the implementation or proposed implementation of HR analytics. The Society of Human Resources Management (SHRM) identifies

two primary objectives of HRA: cost reduction and enhancement of workforce competencies to ensure organizational effectiveness (Huselid, 2018). The conceptual basis of HRA encompasses its definition, strategic significance, methodological frameworks, and the practical and ethical dilemmas related to its execution (Opatha, 2020). Manpower is the largest asset of every organization (Khalil *et al.*, 2023), which is why HRM is a crucial constant support of the growth and success of a firm. With the spread of technology and the reinforcement of rivalry, the business environment and dynamics have become increasingly perplexing. The key concept is that by employing analytics, HRM can make better data-driven decisions and concentrate on the strategic employment of human resources (Erro-Garcés and Aramendia-Muneta, 2023). That is, HRM may leverage the transformative capabilities of various technological components, enhance understanding of multiple challenges, and examine different big data issues (Erro-Garcés and Aramendia-Muneta, 2023). To tackle this complexity, scholars have proposed comprehensive frameworks that emphasize both technical aspects, like data accuracy and analytical software. (Vijay & Raju, 2024) calls for a substantial transition towards ethical, strategic, and proficient HR analytics approaches. Their assertions indicate that the challenges include a shortage of skilled professionals in advanced data analysis, insufficient integration of analytics into standard HR practices, and increasing concerns about privacy and the ethical handling of sensitive employee information (Vijay & Raju, 2024). The use of HR analytics is frequently hindered by significant obstacles, despite its transformative potential. A valid working definition of HR analytics is to define it “as the measurement and assessment of key HR outcomes and workforce qualities to support management and decision making”. It refers to any technique to obtain information about the people in a business and then apply those insights to fulfil corporate goals (Jyoti *et al.*, 2020).

Strategic role and applications of HRA

HRA has evolved from a basic reporting tool focusing on descriptive metrics like demographics, absence rates, and turnover, to a strategic function embedded inside organizational decision-making processes. Some organizations continue to utilize

HR analytics in isolation for administrative insights, while others have started to integrate it with comprehensive predictive and prescriptive models to derive greater organizational value (Arora *et al.*, 2021). This transition signifies an increasing executive desire for data-driven insights to guide workforce planning, succession strategies, and personnel optimization. This progression is not without dispute. Researchers Abellán-Sevilla and Ortiz-de-Urbina-Criado (2023) contend that, while its strategic potential, HR analytics frequently remains underexploited due to cultural opposition within HR departments and a misalignment with business aims. The evolution of conventional HR functions such as recruitment, compensation, and personnel management into data-centric processes has raised concerns about data ethics, privacy, and algorithmic bias, especially in AI-assisted decision-making systems (Alzayed & Al-Hunaiyyan, 2021; Francis *et al.*, 2023). While HR analytics is frequently lauded for enhancing talent distribution and performance assessment (Islam *et al.*, 2022), scholars like Kimura (2023) warn that data quality, contextual comprehension, and organizational preparedness are crucial factors for success. Merely possessing HR data is inadequate; the critical factor is how firms interpret and utilize it within evolving worker contexts. The literature, such as (Arora and Upadhyay, 2024), emphasizes both the potential and the constraints of HR analytics, highlighting the necessity for integrative frameworks that combine technical proficiency with strategic HRM intelligence. The study of (Katfi *et al.*, 2024) provides an extensive examination of HR Analytics, outlining its strategic significance, practical uses, and the requisite cultural transformations for its effective integration in contemporary HRM, however, the paper highlights HR Analytics as a transformative strategy rather than a mere technology tool, necessitating strategic intent, cultural adaptation, and ongoing learning to achieve its full potential in contemporary HRM. Bandi, Rao, and Ali (2021) assert that HR analytics may be categorized into two approaches: the data-driven approach, which is the earlier method, and the business-driven approach, which considers the firms' conditions and the external environment. Some scholars, such as Pape (2016), recommend a data collection framework for 30 types of data to analyse HR activities. The effects of COVID-19 on the workplace increase the need

for a more multidimensional HR strategy (Abellán-Sevilla & Ortiz-de-Urbina-Criado, 2023). Thus, the Employee Experience (EX) Theory in HRM offers a design thinking approach to improve employees' experience in the workplace (Plaskoff, 2017). In addition, resource-based theory and data analytics from Goswami & Mansi. (2025) found a link between Resource-Based Theory (RBT), analytics, employees, and competitive advantage. (Linking the competitive advantage of having talented employees and keeping them. The implementation of HR analytics has risen in prominence since Google introduced the notion of "People Operations". HR analytics is projected to expand by 71% worldwide from 2013 to 2017. Nonetheless, despite the growing enthusiasm and conceptual depth regarding HR analytics, much of the existing literature primarily highlights its strategic advantages without adequately investigating its actual organizational implementation, long-term viability, or impact variability across diverse sectors and cultures.

Empirical findings and global adoption trends

The HR research institute reports that in 2013, 8.6% of participating organizations in the UAE exhibited leading HR analytics performance, whilst 52.4% demonstrated a following performance (Mahmood *et al.*, 2022). Furthermore, the implementation of more sophisticated and accurate HR analytics metrics is anticipated to motivate organizations to adopt optimal practices in this domain (Jyoti *et al.*, 2020). Moreover, the study of Bandi *et al.*, (2021) emphasizes that HR analytics provide decision-making assistance across the employee life cycle, such as in applicant selection, and can offer strategies to bridge discrepancies between requirements and labor capabilities. The implementation of HR analytics and other HR technologies in any firm positively influences employee performance by yielding significant outcomes (Bandi *et al.*, 2021). The study done by Erro-Garcés and Aramendia-Muneta (2023) attempted to assess the influence of data analytics and robots on the performance of organizations throughout Europe. Evidence suggests that Human Resource Management Practices (HRMP) are significant in clarifying organizations' profitability. HR and technology are mutually supportive resources that contribute to generating superior outcomes. A high and statistically significant link was observed

between earnings and the utilization of data analytics for the aim of monitoring employee performance. Furthermore, the analysis demonstrated strong and relevant relationships between human resource practices and profitability. The article provides insights into the impact of technological and human elements on profitability, underlining the importance of human resource strategy and technology in accomplishing organizational goals (Erro-Garcés and Aramendia-Muneta, 2023). Zehir *et al.*, (2020) contend that big data and AI technologies are revolutionizing strategic HRM and influencing corporate performance, while tracking the growth of HR since 1945 and underscoring their importance in contemporary HR responsibilities. Their study examines multiple issues, including the influence of digital technologies on strategic human resource management and the function of big data and artificial intelligence in the strategic advancement of HR. The paper presents frameworks but lacks offering additional empirical evidence or case studies to support its claims. Although useful for synthesizing information and establishing future study priorities, its conceptual character may confine its 'findings' to observations and conversations rather than experimentally validated results. A study conducted by Jyoti *et al.*, (2020) sought to assess the impact of HRM practices on Teachers' Performance through HRA. The findings demonstrate that HR practices, particularly training and development, performance management, performance appraisal, and empowerment, positively influence teachers' performance. However, its cross-sectional design and sampling method limit the generalizability and causal interpretability of its findings, and its narrow focus on teacher performance overlooks broader educational outcomes. Islam *et al.*, (2022) performed a study in Bangladesh to ascertain the principal parameters affecting the use of AI-based technologies in recruitment. The researchers employed the Unified Theory of Acceptance and Use of Technology (UTAUT) model, incorporating perceived credibility and moderating variables as their analytical framework. The study's results demonstrate that all anticipated connections were statistically significant, except for the extended variable of perceived credibility. Nonetheless, there was no indication that gender or firm size exerted any moderating influence on the proposed hypotheses. Kiran *et al.*, (2022) performed a systematic literature review to examine the

relationship between Human Capital Management (HCM), HRA, and Organizational Performance (OP). The authors developed a theoretical framework to examine the relationship between HCM components and their effect on organizational performance, incorporating HR analytics as a mediating factor. The systematic investigation validated the proposed conceptual model and illustrated that HR analytics empower organizations to oversee their human capital management, resulting in improved organizational performance. Nonetheless, their validation method lacks robustness as it mostly relies on synthesizing previous research rather than evaluating the model with empirical data or stakeholder input, rendering it less applicable and more challenging to implement throughout various settings. Furthermore, Huselid's (2018) study shows that workforce analytics helps leaders and managers reach their goals through better staff management. Although analytics has great potential, the study assumes managers can simply analyze complex worker data. This ignores talent gaps, aversion to data-driven organizations, and the ambiguity of translating strategic goals into HR metrics. Despite its insights, the survey may overstate how easy and ready companies are to incorporate employment analytics. In recent years, the labor market dynamics in the Middle East, especially among the Gulf Cooperation Council countries, have seen a substantial transformation (Shayah and Sun, 2019). As oil-dependent economies endeavor to diversify and transition to a knowledge-based economy, the importance of human capital has grown progressively vital (Achoui, 2009). Recent international evidence further underscores the global expansion of HRA. In a study from the UK, Basnet (2024) found that AI-driven predictive analytics significantly improved employee retention by forecasting turnover risks and enabling targeted interventions. Additionally, Alabi *et al.*, (2024) investigated workforce analytics in Nigeria and demonstrated how data-driven insights can elevate customer service and performance strategy through HR practices. These examples illustrate how HRA is being strategically applied across diverse economic contexts to enhance HR effectiveness and organizational outcomes.

Research gaps and future directions

Anand *et al.*, (2023) undertake a bibliometric analysis of HRM with a focus on AI from 2012 to

2023). The study uses trend, theme, performance, cluster, co-citation, and co-occurrence analysis, providing significant perspectives on domestic and international citations and bibliographic linkages. A dataset of 659 Scopus-extracted documents was analyzed using VOSviewer for performance analysis and topic cluster inspection. Moreover, this research furnishes valuable perspectives on both domestic and international citations and bibliographic references that shed light on the significance of artificial intelligence within the realm of human resources. Furthermore, Votto, Valecha, Najafirad, and Rao (2021) argue that the tactical processes of recruitment, employee performance assessment and satisfaction, compensation and benefits analysis, best practice evaluation, disciplinary management, and employee training and development systems have increasingly integrated AI. Consequently, they performed a systematic review to examine published sources and literature about the implementation of AI in HRM. Their study delineates the components of tactical HRM/HRIS that are emphasized and highlights research deficiencies to guide future contributions. In another review, Huang et al., (2023) examined the novel idea of personalized HRM, distinguished by the implementation of sophisticated HR analytics and AI to deliver customized HR solutions. They asserted that Personalized Human Resource Management should be executed at the individual level and signifies the next evolution of HRM. Their research established that Personalized HR surpasses traditional standardized HRM regarding productivity, positive HR atmosphere, adaptability, return on investment in HRM, and overall financial performance of the organization. To achieve these objectives, the authors applied a bibliometric analysis from 2012 to 2024. The strategic importance of HRA is significantly acknowledged; nevertheless, substantial research limitations remain, especially concerning geographical representation, empirical validation, and the utilization of advanced analytics. Contemporary research is primarily focused on developed regions, resulting in a substantial lack of studies from developing areas, which limits a comprehensive understanding of contextual difficulties and the implementation of HR analytics in varied situations (Chhetri et al., 2023). Moreover, despite the numerous proposed conceptual models, there exists a deficiency of empirical research and real-world case studies to substantiate these frameworks

and evaluate their practical relevance (Edwards et al., 2022; Chhetri et al., 2023). Another constraint is the inadequate application of advanced analytics—specifically predictive and prescriptive techniques—despite its capacity to facilitate proactive, data-driven decision-making; the domain continues to be predominantly governed by descriptive and diagnostic methodologies (Jana et al., 2022). The literature inadequately explores the long-term sustainability of HR analytics and its application across many sectors and corporate cultures (Wang et al., 2024). This is exacerbated by insufficiently examined ethical issues, including data privacy and algorithmic prejudice, which are becoming increasingly significant with the expanding incorporation of artificial intelligence into HR systems (Edwards et al., 2022). To address these limitations, researchers are urged to connect theory and practice by situating future studies within actual organizational contexts, emphasizing data quality, contextual comprehension, and ethical considerations (Yin & Gallardo-Gallardo, 2024; Jana et al., 2022). Furthermore, the implementation of longitudinal and mixed-methods research designs will augment causal inference and boost the generalizability of results (Wang et al., 2024). To enhance the field's relevance, rigor, and ethical foundation, it is imperative to advance regional representation, deepen AI integration, and investigate future paradigms like Personalized HR Management.

MATERIALS AND METHODS

Methodology

A comprehensive bibliometric approach was adopted to analyze publication research developments in HRA from 2012 to 2024. The methodology encompassed three key phases: data collection, data processing, and analysis. The following search string was used in the title to ensure relevant and comprehensive coverage of relevant literature: ("Human Resource Analytics" OR "HRA" OR "People Analytics" OR "Workforce Analytics"). The search was confined to documents published between January 1, 2012, and May 1, 2024. Filters were applied to limit results, such as articles, conference papers, book chapters, and review papers. Only documents in the English language were included. The inclusion and exclusion criteria are as follows: All retrieved records were screened by title to ensure relevance to the field of HRA. Publications that did not focus

on analytics applications in human resources were excluded. Duplicate entries and irrelevant records (e.g., those focused solely on general data science without HR context) were manually removed. After screening, 211 documents were retained for analysis. Key variables, such as publication year, source type, author affiliations, citation counts, and keywords, were used for further analysis. This study follows established and rigorous practices in bibliometric research. By adopting frameworks by Zupic and Čater (2014) and Donthu *et al.*, (2021), two main bibliometric techniques were employed, which are (1) Performance Analysis and (2) Science Mapping. In the data analysis stage, the dataset was subjected to descriptive analysis using MS Excel, BiblioMagika, and VOSviewer, a specialized software for constructing and visualizing bibliometric networks. The study conducted four forms of analysis:

(1) *Citation Metrics Analysis.*

(2) *Co-authorship Analysis to identify influential authors and their resulting network of collaboration.*

(3) *Co-citation Analysis to map the citation network relationship of the field.*

(4) *Keyword Co-occurrence Analysis was conducted to generate themes and research trends.*

The resulting visualizations were examined to analyze author collaborations, research clusters, and keyword relationships, providing insights into the interconnectedness of the various research themes. These findings were done to ensure a comprehensive understanding of the research landscape. This bibliometric study enabled a robust examination of the evolution, influence, and future trajectories of

HRA research. This study applied good practices in bibliometric methodology based on previous studies (Wider *et al.*, 2024a; Wider *et al.*, 2024b).

RESULTS AND DISCUSSION

Main information

The citation metrics (Table 1) on Human Resource Analytics publications from 2012 to 2024 indicate a significant intellectual contribution stemming from a growing interest in this field. A total of 211 publications have been generated over a 13-year time frame. This points to a consistent research output. There were 602 contributors, with an average of 2.85 authors per paper, reflecting a high level of collaboration. The analysis uncovers 2,674 citations with an average of 12.67 citations per paper. In addition, the citation rate for the 148 cited papers is higher, at 18.07 citations per cited paper. This suggests the influence of selected works. The generated h-index of 24 reflects that at least 24 papers have received 24 or more citations, showing a resounding academic impact. The g-index of 47 suggests that the top 47 papers together received at least 47 (2,209) citations, representing the broad reach of highly cited papers in the domain. The citation sum within the h-Core is 2,395, revealing that a large portion of the total citations is contributed from a small number of papers. The m-index, at 1.846, implies steady research productivity and influence over time. While the citation metrics provide a strong descriptive overview, they also offer deeper insight into the publication dynamics of the HRA field. The relatively high h-index (24) and m-index

Table 1: Citation metrics

Main Information	Data
Publication Years	2012 - 2024
Total Publications	211
Citable Year	13
Number of Contributing Authors	602
Number of Cited Papers	148
Total Citations	2,674
Citation per Paper	12.67
Citation per Cited Paper	18.07
Citation per Year	222.83
Citation per Author	4.44
Author per Paper	2.85
Citation sums within h-Core	2,395
h-index	24
g-index	47
m-index	1.846

(1.846) critically underscore consistent productivity over time. This strongly suggests that HRA is shifting from an emerging topic to an established research area. The skewed distribution—with most citations coming from a small set of highly cited papers reflects a core academic structure. This suggests that only a few seminal studies dominate the HRA literature.

This pattern underscores the need for diversification in theoretical perspectives and more distributed contributions from a broader range of scholars and institutions.

Annual publication trends

Based on Table 2 and Fig. 1, the annual publication

Table 2: Publication by year

Year	TP Total Publication	NCA Number of authors	NCP No. cited paper	TC Total citation	C/P Citation per paper	C/CP Citation per cited paper	H H-index	G g-index	M m-Index
2012	3	7	3	242	80.67	80.67	3	3	0.231
2014	2	4	2	29	14.50	14.50	2	2	0.182
2015	1	2	1	188	188.00	188.00	1	1	0.100
2016	3	5	3	55	18.33	18.33	3	3	0.333
2017	15	32	13	608	40.53	46.77	7	15	0.875
2018	4	10	4	78	19.50	19.50	3	4	0.429
2019	8	17	6	126	15.75	21.00	4	8	0.667
2020	16	46	16	215	13.44	13.44	7	14	1.400
2021	18	49	17	377	20.94	22.18	9	18	2.250
2022	26	70	23	362	13.92	15.74	9	18	3.000
2023	57	163	38	281	4.93	7.39	9	15	4.500
2024	58	197	22	113	1.95	5.14	6	8	6.000
Total	211	602	148	2674	12.67	18.07	24	47	1.846

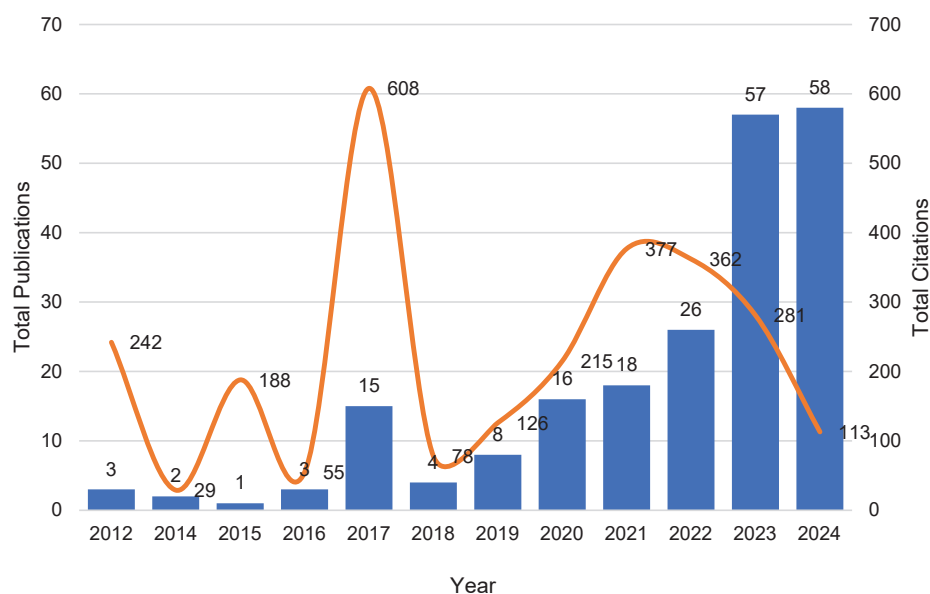


Fig. 1: Total publications and citations by year

and citation trends from 2012 to 2024 reflect a dynamically evolving field in HRA. The early years show low publication numbers, probably indicating limited academic interest. However, a sharp growth from 2016, leading to a peak in 2023 and 2024 with 57 and 58 publications respectively, signifies a major shift in the field. This suggests that HRA has moved to a mainstream research topic, driven by increased recognition of its role in contemporary HR practices. The parallel growth in citations points to a developing field, where seminal research is being extensively referenced. The parallels between the growing publications and citations imply that contributions are not only in numbers but are also considered highly impactful. This underscores HRA's critical role in HR decision-making in the dynamic business field.

Fig. 2 depicts the cumulative total number of publications on HRA from 2012 to 2024. The graph shows a polynomial growth trend, as

evidenced by the equation provided in the chart: $y = 2.5062x^2 - 16.333x + 28.159$ with a commendable coefficient of determination ($R^2 = 0.9705$). This indicates that the polynomial model fits the data very well, capturing 97% of the variance in the cumulative publication trend over the years. Overall, this visualization signifies that HRA is experiencing accelerated growth and is becoming a significant area of research in the academic field.

Documents profiles

Based on Table 3 below, it indicates that researcher in HRA demonstrates a strong inclination for journal articles (53.08%) with 112 publications. Conference papers account for 25.12% (53 publications), suggesting active academic discussions at conferences. Book chapters constitute 12.80% (27 publications). This breakdown suggests that the primary medium for disseminating research is journal

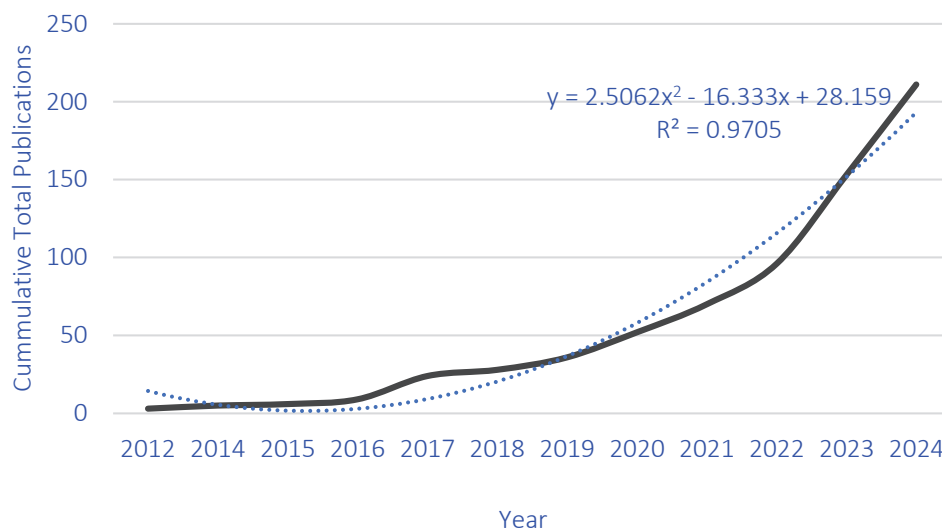


Fig. 2: Cumulative Total Publications by Year (Source: Generated by the authors using biblioMagika®)

Table 3: Document type

Document Type	Total Publication	Percentage (%)
Article	112	53.08%
Conference Paper	53	25.12%
Book Chapter	27	12.80%
Review	14	6.64%
Book	4	1.90%
Short Survey	1	0.47%

Table 4: Source type

Source Type	Total Publication	Percentage (%)
Journal	127	60.19%
Conference Proceeding	36	17.06%
Book	27	12.80%
Book Series	21	9.95%

Source: Generated by the authors

Table 5: Languages

Language	Total Publication	Percentage (%)
English	209	99.53%
Croatian	1	0.47%
German	1	0.47%

Source: Generated by the authors

articles, seconded by conference contributions, reflecting that both in-depth studies and active research discussions are the preferred channels for HRA.

Table 4 shows that for source types, journals are the dominant channel, contributing 60.19% (127 publications) of the total. The second most preferred channel is Conference proceedings, constituting 17.06% (36 publications), highlighting its substantial engagement in academic conferences. Books account for 12.80% (27 publications), and book series account for 9.95% (21 publications). This breakdown suggests that journals are the primary preference for research dissemination, while conferences and books also play a secondary supportive role in expanding scholarly engagement in this field.

Table 5 shows a strong preference for English, accounting for 99.53% (209 publications) of the total. Croatian and German each contribute only 0.47% (1 publication each). This underscores the dominance of English, highlighting its role as the primary language for academic communication in this field, suggesting that English allows a wider accessibility and global reach for academic researchers. Thus, it can be critically inferred that near-exclusive use of English as a publication language reveals both global accessibility and a noticeable potential bias that could limit regional diversity.

Table 6 below suggests that HRA is a highly interdisciplinary field with its intellectual roots in Business, Management, and Accounting. This is evidenced by 63.98% of the publications in these

areas. Closely related is the substantial presence in Computer Science (34.60%) and Engineering (21.80%). This only shows that HRA has a strong reliance on technical and computational methods. The diverse subject area spread underlines the fact that HR Analytics is not only concentrated in traditional HR disciplines but covers various fields, which allows it to leverage insights from multiple areas to propel data-informed decision-making in organizations.

Most productive authors

The bar chart in Fig. 3 represents the most productive authors in HRA. Prolific researcher Mittal, A., professor of management at Chitkara University, has one of his research interests in employability, with 7 documents, followed by Arora, M., with 6 publications. Prakash, A., Singh, S., and Cavanagh, J. each have 5 publications. The involvement of several authors with 4 to 6 publications suggests that a small core group of researchers drives most of the development in this field. This concentration may imply that collaborations and citations within this group are probably high, leading to the field's growth and also providing seminal work for emerging researchers.

Most productive institutions

Fig. 4 bar chart shows that the most productive are Chitkara University, Punjab (8 documents), followed by Amity University (6 publications). K.R. Mangalam University and Bharatiya Vidya Bhavan's

Table 6: Subject area

Subject Area	Total Publication	Percentage (%)
Business, Management, and Accounting	135	63.98%
Computer Science	73	34.60%
Engineering	46	21.80%
Decision Sciences	35	16.59%
Social Sciences	30	14.22%
Economics, Econometrics, and Finance	27	12.80%
Mathematics	22	10.43%
Psychology	19	9.00%
Physics and Astronomy	7	3.32%
Environmental Science	5	2.37%
Medicine	5	2.37%
Energy	4	1.90%
Agricultural and Biological Sciences	3	1.42%
Multidisciplinary	3	1.42%
Materials Science	2	0.95%
Arts and Humanities	1	0.47%
Biochemistry, Genetics, and Molecular Biology	1	0.47%
Chemical Engineering	1	0.47%
Neuroscience	1	0.47%
Nursing	1	0.47%

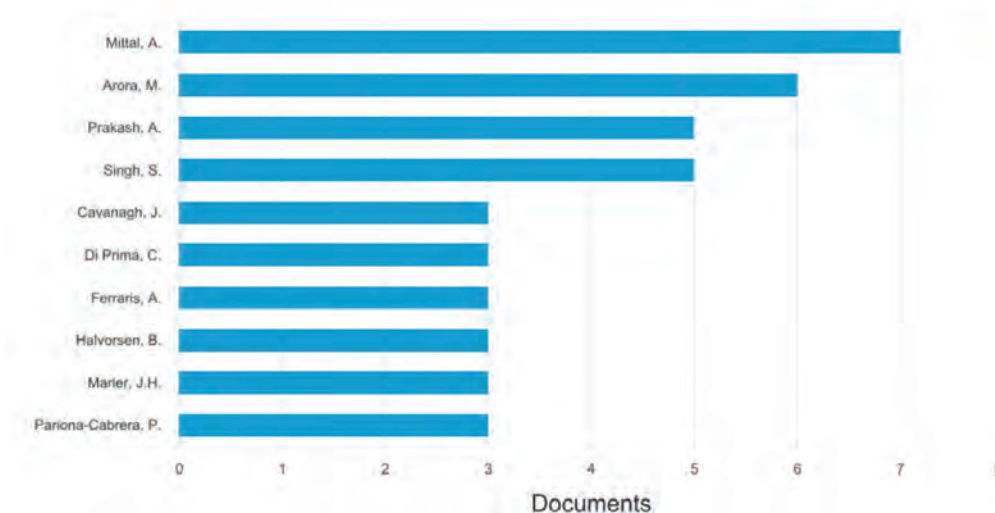


Fig. 3: Most productive authors

Usha and Lakshmi Mittal Institute of Management each contributed 5 publications. RMIT University and the State University of New York, Albany have 4 publications. The chart shows that 6 out of 10 top institutions in the bibliometric analysis are Indian institutions. The bibliometric analysis shows that Indian institutions are contributing strongly to the academic knowledge base of this search analysis. Furthermore, a systematic literature

review conducted by [Chhetri et al., \(2023\)](#) argues that most of the HRA research originates from India. The active involvement of these institutions suggests a growing focus on analytics in the HR field in India. The active engagement of global institutions such as RMIT and the State University of New York, Albany, suggests that research in HRA is not limited to a specific geographical region but is gaining global interest.

Most productive countries

Fig. 5 displays the top 10 countries contributing to HRA research from 2012 to 2024. India's contribution is significantly high, with close to 90 publications, trailed by the United States with almost 40 publications. Germany, Australia, and contributions are lower, ranging between 10 and 15. China, the United Kingdom, the Netherlands, the Russian Federation,

and Spain each have fewer than 10 documents. This spread of publication again suggests that Indian is the lead contributor for HRA publications. The dominance of India may be influenced by the pressing demand for HRA in developing economies to optimize talent management and organizational efficiency. The added contribution by European and Asian countries reflects the field's growing international interest and

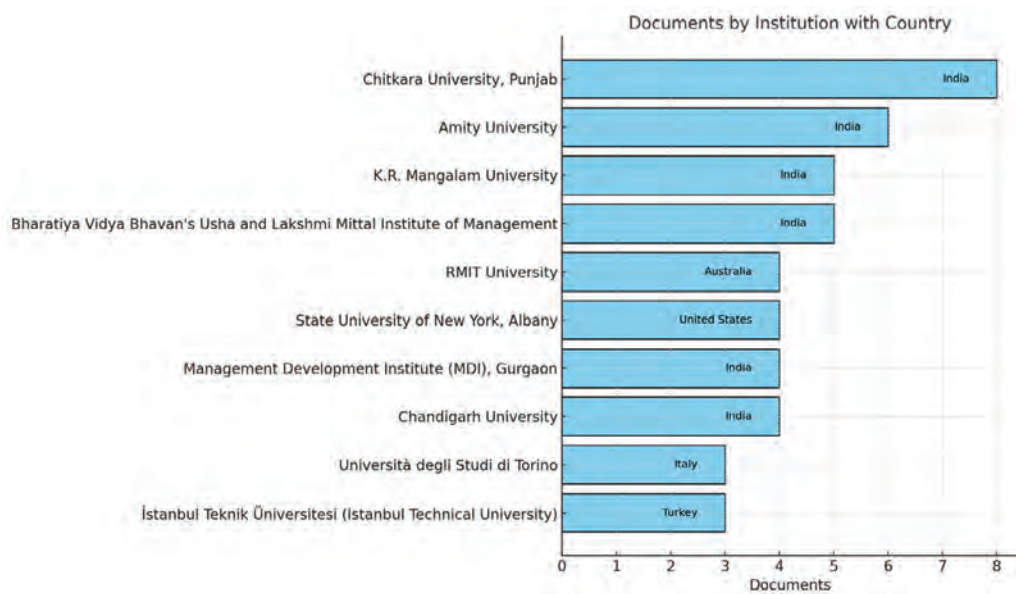


Fig. 4: Most productive institutions with a minimum of three publications

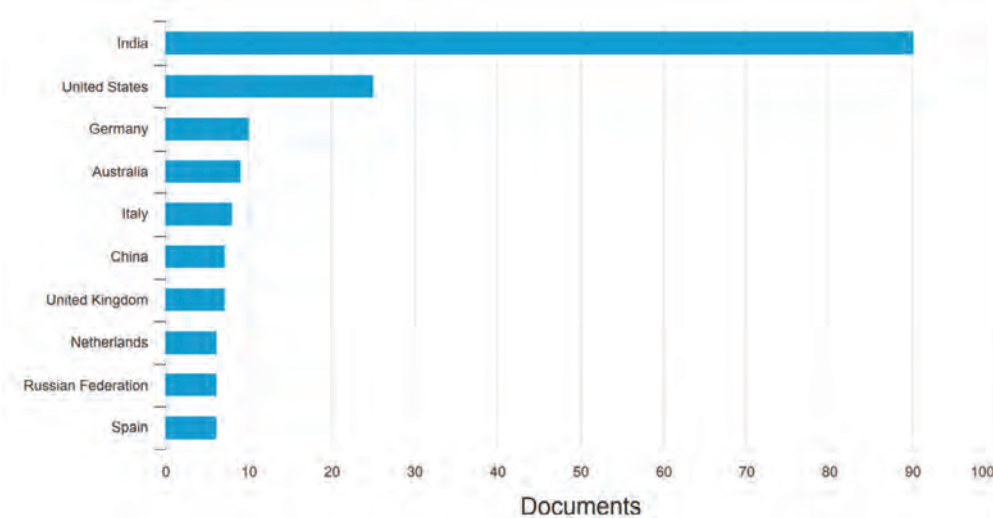


Fig. 5: The top 10 countries contributed to the publications.

Table 7: Top 10 most active source titles

Source Title	TP	NCA	NCP	TC	C/P	C/CP	<i>h</i>	<i>g</i>	<i>m</i>
Lecture Notes in Networks and Systems	9	34	3	5	0.56	1.67	1	2	0.333
HR Analytics in an Era of Rapid Automation	7	16	2	21	3.00	10.50	2	4	1.000
Personnel Review	7	18	7	164	23.43	23.43	4	7	0.667
Management Decision	5	17	5	90	18.00	18.00	3	5	0.750
Journal of Organizational Effectiveness	5	14	3	132	26.40	44.00	2	5	0.250
International Journal of Human Resource Management	4	11	3	423	105.75	141.00	3	4	0.375
Human Resource Management International Digest	4	0	2	7	1.75	3.50	1	2	0.077
Human Resource Management Journal	4	13	4	102	25.50	25.50	4	4	0.800
International Journal of Manpower	3	11	3	65	21.67	21.67	2	3	0.667
Benchmarking	3	9	3	22	7.33	7.33	3	3	1.500

Table 8: Top 15 highly cited articles

No.	Author(s)	Source Title	TC	C/Y
1	Marler J.H.; Boudreau J.W. (2017)	International Journal of Human Resource Management	336	42.00
2	Aral S.; Brynjolfsson E.; Wu L. (2012)	Management Science	209	16.08
3	Rasmussen T.; Ulrich D. (2015)	Organizational Dynamics	188	18.80
4	van den Heuvel S.; Bondarouk T. (2017)	Journal of Organizational Effectiveness	123	15.38
5	Margherita A. (2022)	Human Resource Management Review	112	37.33
6	Fernandez V.; Gallardo-Gallardo E. (2021)	Competitiveness Review	100	25.00
7	(Chalutz Ben-Gal, 2019)	Personnel Review	84	14.00
8	(Dahlbom, Siikanen, Sajasalo, & Jarvenpaa, 2020)	Baltic Journal of Management	66	13.20
9	(Vargas, Yurova, Ruppel, Tworoger, & Greenwood, 2018)	International Journal of Human Resource Management	65	9.29
10	(McCartney & Fu, 2022)	Management Decision	62	15.50
11	(Sharma & Sharma, 2017)	Management Research Review	59	7.38
12	(Qamar & Samad, 2022)	Personnel Review	57	19.00
13	(Falletta & Combs, 2021)	Journal of Work-Applied Management	50	12.50
14	(Chatterjee, Chaudhuri, Vrontis, & Siachou, 2022)	International Journal of Manpower	48	16.00
15	(Tunsi et al., 2023)	Information Sciences Letters	43	21.50

the broadening appeal of HRA research across diverse communities globally.

Publications by source titles

Table 7 shows the top 10 most active source titles in HRA research, with Lecture Notes in Networks and Systems as the most active, with 9 publications, but with a low citation impact (C/P = 0.56). HRA in an Era of Rapid Automation and Personnel Review both contribute 7 publications, with Personnel Review showing a significant influence (TC = 164 and C/P = 23.43). Management Decision and Journal of Organizational Effectiveness have 5 publications each, but the Journal of Organizational Effectiveness has a higher citation per paper (C/P = 26.4). This finding suggests that research on HRA is not solely dependent on the volume of publications but also on the quality of the content.

Highly cited documents

Table 8 below records that the most cited article is Marler & Boudreau (2017)'s "An evidence-based review of HRA" in the *International Journal of Human Resource Management*, with 336 citations (C/Y = 42.00), underscoring its impact in the HRA field. Aral, Brynjolfsson, & Wu (2012)'s "Three-way complementarities" in *Management Science* follows with 209 citations, revealing the importance of integrating HR analytics with other organizational practices. Other notable contributions from (Rasmussen and Ulrich, 2015) and (van den Heuvel and Bondarouk, 2017) also receive high citations, indicating strong interest in understanding the practical application of HRA. These results suggest that highly cited papers tend to focus on strategic frameworks, practical implementation, and barriers to HRA adoption, making them critical references for future research.

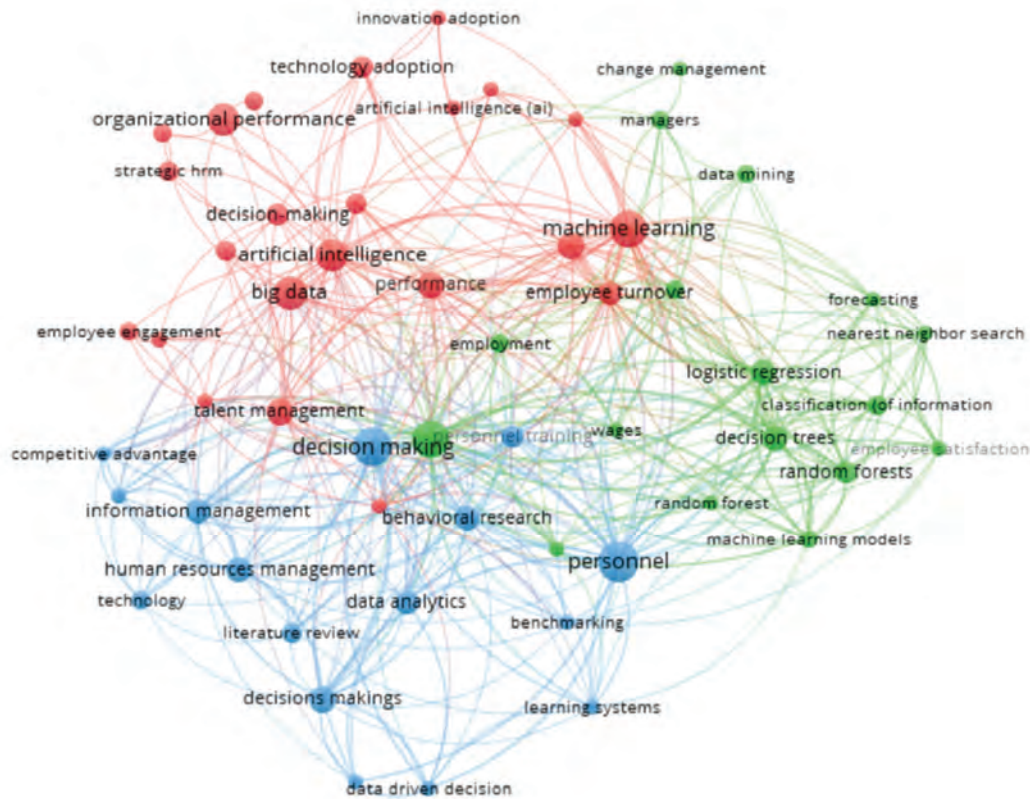


Fig. 6: Keyword co-occurrence network

Keyword analysis

Fig. 6 below depicts a keyword co-occurrence network graph generated using VOSviewer. The network graph illustrates the thematic patterns generated from frequently occurring keywords in Human Resource Analytics research. Nodes symbolize keywords, with size indicating frequency and links reflecting co-occurrence relationships. Three primary clusters are visible, reflecting key themes within the HRA literature. The **Red Cluster** is reflected by terms such as *machine learning*, *big data*, *technology adoption*, and *AI*. This cluster highlights the emphasis on advanced analytics technologies within HR practices, suggesting an inclination toward using AI and machine learning tools to enhance HR practices. It shows a strong shift towards data-driven decision-making in HR. The **Green Cluster** contains keywords such as *logistic regression*, *decision trees*, and *classification*. The keywords represent the technical focus on predictive modeling. These specific keywords suggest a focus on statistical analytical

techniques to generate insights from HR data. The **Blue Cluster** focuses on traditional HR functions with keywords such as *HRM*, *decision making*, and *behavioral research*. This cluster reflects the use of various forms of analytical techniques to aid HR-related decisions, such as performance management and employee retention. The central positioning of keywords like *machine learning* and *decision-making* highlights a substantial overlap between clusters, implying that technology-driven analytics are deeply connected with practical HR applications. The graph depicts that HRA is increasingly reliant on data-centric approaches to address traditional HR challenges. This signifies the convergence of technical approaches and managerial applications, making HRA a critical component in enhancing organizational performance and competitive advantage. The keyword clusters analysis critically suggests distinct theoretical foundations. The Red Cluster, as shown in the figure below, depicts data science and technology disciplines by its focus on AI and machine learning.



Fig. 7: Co-authorship analysis

The prominent Green Cluster underlines quantitative modeling. In contrast, the Blue Cluster reflects traditional HR and behavioral theories with a focus on decision-making and workforce practices. The central positioning of concepts such as decision making and machine learning highlights a growing interdisciplinary integration. The clustering below shows a pressing need for more cohesive and cross-disciplinary research in HRA.

Co-Authorship Analysis

Fig. 7: Co-authorship network graph depicts the collaborative relationships among researchers in the HRA field. Each node symbolizes an individual author, and the lines show co-authorship relationships, with thicker lines indicating stronger collaborations. The network presents that **Amit Mittal** serves as the central figure connecting these groups. There are two noticeable clusters. The first cluster includes **Swati Singh**, **Meenal Arora**, and **Prakash Hanshika**, who are closely connected, indicating a strong internal collaboration, where this small group of authors frequently publishes together. In contrast, the second cluster consists of **Teena Bagga**, **Sangeeta Gupta**, and **Mansi Saxena**, who display fewer interconnections. Amit Mittal bridges these two clusters, highlighting his influence in fostering working collaboration across different research clusters. Mittal's central position in the network suggests that he is a key researcher who is facilitating the flow of knowledge, which will enhance interdisciplinary collaboration and contribute significantly to the dissemination of research within HRA.

Citation analysis on documents

Fig. 8 citation network graph provides an overview of the citation relationships among highly cited documents. Each node here represents a document, and its size demonstrates the number of citations it has received. Links between nodes show citation relationships, and the different colors signify distinct research clusters. The graph displays three main clusters. The Yellow Cluster, dominated by **Marler (2017)** and **Aral (2012)**, represents foundational papers that have heavily influenced research. Their work, respectively, on evidence-based review of HRA and integrating HRA with performance management and information technology, has broad citation links, indicating that they serve as key references for other studies. The Red Cluster is centered around **(Fernandez and Gallardo-Gallardo, 2021)** and **(Margherita, 2022)**. This cluster focuses on systematizing research topics in HR analytics and barriers to HR digitalization. It suggests a focus on key topics in HRA and a strong focus on adoption and implementation challenges faced by organizations. The Green Cluster revolves around **(Greasley and Thomas, 2020)** and **(Gurusinghe et al., 2021)** practice-based research, respectively, on the influence of analytics projects on professional practice and predictive HRA. The recency of their work in this cluster suggests ongoing developmental research in practical applications.

Limitations of the study

Despite the detailed and comprehensive nature of bibliometric analysis, this study comes with some limitations. First, the data used in the analysis is

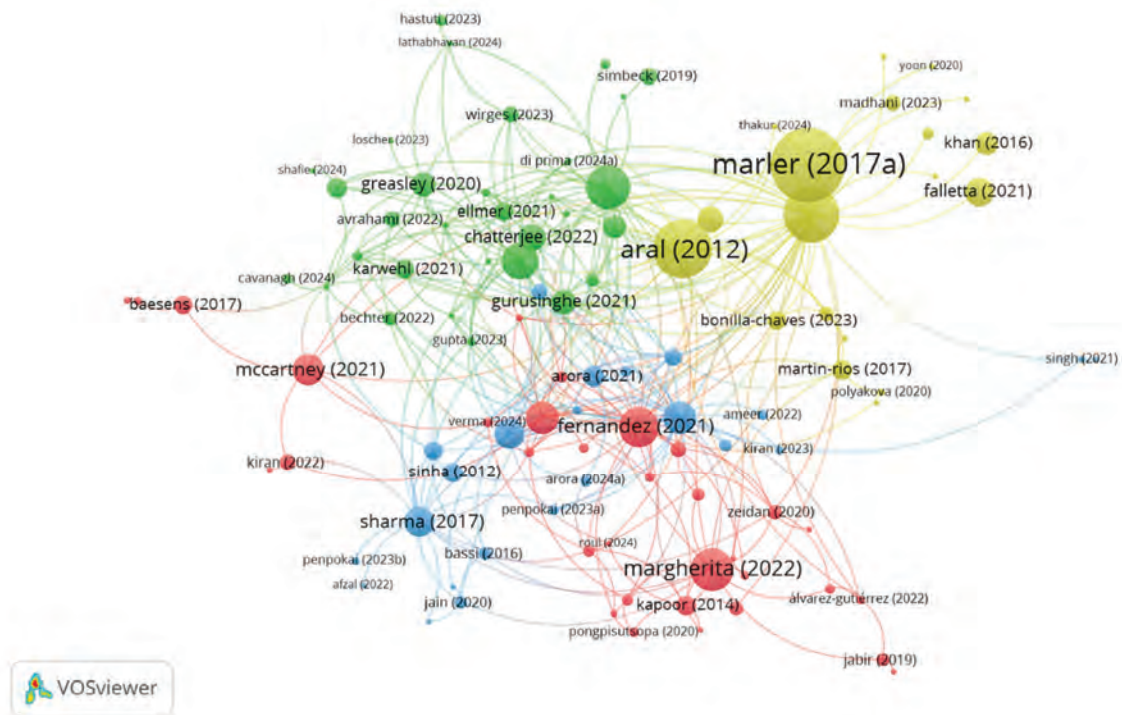


Fig. 8: Citation analysis on documents

limited to the Scopus database, which does not cover all publications in HRA. Second, the overt focus on citation metrics can lead to biases, where more established and foundational works may be sidelined compared to recent contributions that have gained faster traction. Additionally, the use of scientific visualization centered on keyword co-occurrence and citation analysis has its drawbacks. While it is effective in identifying key themes and influential works, it may not fully capture the actual developments within the field in various organizational settings. The analysis primarily focuses on quantitative measures, thus overlooking qualitative insights that may provide deeper insights into how HRA is evolving in practice. Finally, the analysis of co-authorship networks is limited to only the recorded publications of collaborations. Consequently, this form of analysis will not account for informal or interdisciplinary work. Future studies could address these gaps by applying qualitative methodologies and including various databases and their datasets to include wider sources and insights, thus providing a more holistic view of the development and challenges in this field.

Future research directions

The evolving landscape of HRA presents several promising avenues for further investigation. Building on the cluster analysis conducted in this study, future research should delve into the integration of advanced technologies such as AI and machine learning within conventional HR functions. These tools hold the potential to significantly enhance accuracy in areas like talent acquisition and employee performance assessment. Moreover, there is a pressing need to explore the ethical and privacy-related implications of using digital technologies in HR, an area that continues to pose significant challenges. Value-driven studies could also employ analytics to track and evaluate HR practices, thereby enhancing organizational effectiveness. Another critical direction involves examining how HRA can support strategic decision-making and contribute to long-term workforce sustainability in a competitive and rapidly changing environment. Encouraging interdisciplinary collaborations between HR professionals and data scientists may lead to the creation of more robust and practically viable HRA frameworks. Such collaboration

is important for moving beyond analytics to aligning HRA initiatives with overarching organizational strategies. Ultimately, future studies should focus on narrowing the gap between technological innovation and its practical implementation, ensuring that HRA contributes meaningfully to achieving strategic business objectives. Future research may also consider expert validation or integrating qualitative techniques—such as thematic analysis of full-texts or interviews with HRA practitioners—to triangulate findings and enhance contextual relevance.

CONCLUSION

In conclusion, the bibliometric analysis of HRA research from 2012 to 2024 uncovers a steady growth and evolution of studies in this field. The analysis yields 211 publications from 602 contributing authors. These publications generated 2,674 citations. The average citation per paper is 12.67, the cited papers are 18.07, per year is 222.83, and per author is 4.44. The analysis managed to have an h-index and a g-index of 24 and 47, respectively. The growth of publications shows a parallel growth in citation metrics, suggesting a consistent interest and influence of HRA on academic research. The field has seen notable contributions from small core groups of authors, institutions, and countries, establishing a well-developed foundation for future research. Visualization mapping techniques using keyword co-occurrence network revealed three core clusters. These clusters have narrowed to themes centered around machine learning and artificial intelligence. Additionally, the keywords such as *decision making* and *organizational performance* signify a strategic shift towards integrating HRA with traditional HR practices. This suggests a focus aimed at improving the decision-making processes. The co-authorship analysis shows that collaboration is concentrated around a core group of researchers. This core group is dominated by a few central figures, such as Amit Mittal, who acts as a conduit in promoting interdisciplinary research and knowledge exchange. Preceding citation analysis highlighted influential works, such as those by Marler (2017) and Aral (2012), as highly influential, evidence-based reviews of HR Analytics and integrating HRA with performance management and information technology, which have broad citation links, indicating that they serve a key role in shaping the discourse on HR Analytics. Overall, the

bibliometric analysis underscores the growth of HRA. HRA has evolved into a multidisciplinary field that blends technical and organizational perspectives. The blend of technical approaches and traditional HR in decision-making has positioned HRA as a critical tool in enhancing overall organizational performance and its competitiveness. This study offers key implications for both researchers and practitioners in HRA. The emergence of key themes like machine learning, AI, and decision-making implies a progressive shift toward data-driven HR policies and strategies. Future research should develop academic frameworks that combine technical tools with practical HR applications. In addition, the dominance of a small group of authors highlights the implications for broader collaboration with diverse perspectives. Finally, strong citation network clusters suggest a solid theoretical base. This implies opportunities to expand into areas such as ethical AI and cross-functional analytics. These insights can help practitioners better align analytics with strategic HR functions and guide scholars toward future research directions.

AUTHOR CONTRIBUTIONS

First Author: Initiated and framed the core research idea; developed the conceptual and theoretical underpinnings; carried out the systematic literature review; designed the bibliometric methodology; performed the main data collection and analysis; and led the drafting of the manuscript. Second Author: Contributed to refining the research design; assisted in data collection, cleaning, and preprocessing; provided constructive feedback during the analysis stage; and participated in reviewing and editing the manuscript. Third Author: Supported the interpretation of bibliometric results and preparation of visualizations (e.g., co-authorship networks, keyword clusters); contributed to structuring the Results and Discussion sections; and assisted in manuscript revisions. Fourth Author: Coordinated overall project administration; facilitated access to necessary resources and data; ensured alignment of the study with broader scholarly debates in HRM; and contributed to the final critical review and refinement of the manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

AI	Artificial Intelligence
HCM	Human Capital Management
HRA	Human Resource Analytics
HRM	Human Resource Management
HRMP	Human Resource Management Practices

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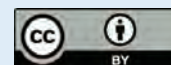
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ORIGINAL RESEARCH PAPER

Connectivity, Integration, and Entropy measurements to assess: Visual perception of city users, urban quality, and growth

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ABSTRACT

BACKGROUND AND OBJECTIVES: Batna city's road network has evolved due to various factors, particularly residents' practices and movements, which have shaped the city's routes and spatial hierarchies. However, the logic of urban production has been unexplored through the prism of user experience. This study aimed to analyze the spatial configuration of the city's road network, to identify the mechanisms driving the city's evolution, highlighting the users' contribution, providing guidelines for future, thoughtful urban planning, and enhancing the quality of urban space by reconciling city users' perception with different approaches to planning.

METHODS: The study applied space syntax Analysis, using depthmap 10 software. It calculated the following parameters: Connectivity, integration, and entropy, and analyzed 25753 axes of Batna's road network. These measures allowed understanding users' perception of accessibility, movement, and route choices. This analysis was complemented by a sociological study and field observations. To assess the robustness of the relationship between these parameters, statistical tests were performed, including Pearson and Spearman correlations, as well as a linear regression test analyzed through the ANOVA table, to examine the relationships between two dualities: connectivity/integration and connectivity/entropy.

FINDINGS: Connectivity values in Batna city ranged from 0 to 7, with higher values (4-7) found in formal districts. The average integration value was 1.17, peaking at 2.63. Pearson and Spearman confirmed strong correlations between these attributes (p-value less than 0.001), while the ANOVA table from linear regression predicted 14% of the variance in Integration. These values revealed areas with high centrality and accessibility, aligning with the questionnaire responses on urban dynamics and frequency. The analysis also recorded high spatial choice and complexity, revealed by a maximum entropy value of 1.057, observed in more than 25753 spatial units analyzed in this study.

CONCLUSION: The study was distinguished by the inclusive approach, based on the exhaustive analysis of the road structure of Batna city. It highlighted that urban quality and perception, although immaterial and subjective concepts, can be objectified and analyzed rigorously. It advocated for urban planning that is more sensitive to spatial configuration. This study was unique in that it analyzed the entire road network of the city, thus providing a solid basis for testing, in future research, other parameters derived from the Space Syntax method.

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INTRODUCTION

In the current context of urban development, interactions between urban users, communities, and the changing environments are emerging as a central issue, highlighting the importance of integrating lived experiences into urban transformation processes. Regardless of scale, each intervention, whether large or small, contributes actively to the ongoing Production of the Urban Space (PUS) (Gu, 2019). In Algeria, the recent transformations and the rapid Urban Growth (UG) impacted the resources and lifestyles of the inhabitants, leading to a review of urban policy, actions, and behaviors within the city. The Quality of the Urban Space (QUS) is now seen as a crucial driver of development, but continues to elude consistent large-scale measurement due to persistent ambiguities for assessing how it is perceived by urban dwellers (Olorunfemi and Adeniran, 2020). Recent studies call for innovative methods to deepen the understanding of these interrelations (Han et al., 2023; Lei et al., 2024), particularly in addressing challenges related to Urban Configuration (UC) (Yadav and Gupta, 2021). The link between the QUS and the physical components of the urban space remains largely underexplored. Architects and urban planners must analyze and foresee the evolution of these components, integrating the perceptive experiences of urban users. The Urban Reality (UR) shaped by the actions of inhabitants and visitors in appropriating urban spaces deserves attention (Khainnar, 2021; Lübcke et al., 2011). Spatial configuration plays a decisive role in the PUS and QUS. By avoiding restricting the analysis to perceptual experiences alone, this study focuses on objectively Measurable and Quantifiable Indicators (MQI), such as connectivity, integration, and entropy of Space Syntax Theory (SST), which directly influence the functioning and navigation of urban spaces. Road Networks (RN), in particular, structure these dynamics. In Batna city, both planned and unplanned RN shape accessibility and mobility; planned urban structure reflects formal design principles, while unplanned networks emerge from users' practices. The city of Batna has been chosen, within the diverse urban contexts of Algeria, for several reasons. Located in the eastern Highlands, it plays a strategic position linking the northern coastal zones and the Saharan territories. Unlike coastal metropolises, Batna exemplifies the challenges faced by interior cities that are experiencing rapid

and uneven urban expansion. Consequently, an investigation yields valuable insights into the broader processes influencing medium-sized cities in Algeria. Therefore, the main questions asked in this study are as follows: What is the spatial configuration of Batna city? Where are the main areas of the city likely to attract people, both residents and visitors? How do these urban dynamics influence urban production, spatial quality, and urban experiences, including the perception of users and urban flows? Knowing that inquiries regarding the QUS are connected to how humans visually perceive it, which in turn influences pedestrian movement, especially since this category encompasses all types of urban users. This study investigates how UC is linked to PUS, UG, QUS, human visual perception, and movement by combining Space Syntax Analysis (SSA) with statistical tests, including Pearson and Spearman correlations and Analysis of Variance ANOVA from linear regression tests. Complemented by a social survey, this study explores various urban environments, particularly the entrances of the city, dominated by an organic urban fabric and the planned city's core. Based on these reflections, the study relies in particular on the following hypotheses:

-The visual perception of city users is influenced by several factors, including the spatial configuration. Therefore, both can be analyzed, predicted, and measured.

- Batna city's core, a highly connected central space, generating a higher potential for pedestrian flow, as well as a visually appealing and well-structured urban space, can influence the overall perception and interaction within the city, and these urban dynamics define the quality of the whole city.

-The neighborhoods, including those of an informal nature or located in the outskirts, that have successfully coordinated internal mobility effectively have met the expectations of urban users, and they are often referred to as quality urban spaces.

This study aims to precisely analyze how the UC of the city of Batna influences the urban dynamics within current residential districts, in particular through the parameters of connectivity, integration, and entropy. The research also seeks to predict potential transformations in Batna's urban morphology by studying the logic of the spatial presence and movement of users within the city. Additionally, this study aims to provide a comprehensive analysis of

all the neighborhoods in the city of Batna, without separating the spaces, and considering them as fragmented entities. The objective is thus to build an integrated understanding of the urban structure of the city. The proposed methodological approach provided an objective analysis of accessibility, legibility, and spatial hierarchy, supporting a rigorous study of the Batna case, conducted in 2024.

Literature review

Indicators of urban structure about scale of analysis: human dimension and street-level dynamics:

The processes of PUS have been mainly studied by different researchers, highlighting the complexity of contemporary urban dynamics (Hersous *et al.*, 2023; Robertson and Neuhaus, 2024; Yu *et al.*, 2023). Over the last few decades, UG has been shaped by intense competition between cities (Hoornweg *et al.*, 2007; B. Huang *et al.*, 2020; Talukder *et al.*, 2025), with urbanization emerging as the structuring force of modern society (Huang *et al.*, 2025; Lakjaa, 2016). Successful UG has always required structured physical planning, an effective system of public spaces, and well-connected RN (Karssenbergh, 2016). These elements affect the overall image of the city (Danese *et al.*, 2009). However, Le Corbusier advocates an organic and decentralized approach in the creation of urban structures, warning against the rigid designs of architects that ignore the complexity of social interactions. Because as long as there are dynamics of daily life in urban spaces, visions about urban planning differ, and the criteria of QUS are constantly evolving (Alexander *et al.*, 1977; Lakjaa, 2016). Pedro Gomes (2017) emphasizes the central role of urban public spaces, in particular RN, in the PUS in Western Europe, also constituting a dimension of public action. Similar to the majority of Mediterranean cities, the main hub for socializing is the street, it structured around public services, local shops, and the multitude of restaurants and cafes, along with the various events taking place there (Barakat and Chamussy, 2002). As a system of alternative routes, it contributes to the readability of the city, facilitating the overall understanding of the urban fabric. Consequently, this dimension must maintain reasonable flexibility, allowing great latitude in the development of space planning solutions. This urbanization also does not cancel the roles of city users. Investigating users' visual perception

preferences concerning urban public space contributes to an understanding of the interplay between the structural dynamics of the PUS and everyday practices that contribute to urban reconfigurations. This improvement encourages social interactions while promoting balanced and sustainable UG, rooted in community well-being and the attractiveness of the living space (Jalaladdini and Oktay, 2012; Peng *et al.*, 2025). These alterations throughout the years have reshaped the idea of what constitutes QUS, in light of social dynamics (Chen *et al.*, 2016; El Sharnouby, 2019; Hall and Pfeiffer, 2013; Huang *et al.*, 2020; Mebirouk, 2019; Rolland, 2022). Acknowledging the active participation of urban users within the context of extensive urbanization serves as a crucial foundation for adopting a more inclusive and participatory framework in urban planning. From this perspective, the RN constitutes a fundamental element of mediation between planning and use, since it structures not only mobility but also the forms of appropriation of space by users. Over the past decades, the city of Batna has experienced significant changes on a major scale in the layout structure, redefining the urban landscape. The central area of the city evolved, often with a concentration of economic and cultural functions, while the urban periphery developed rapidly, leading to forms of urban sprawl and uncontrolled densification, also leading the city toward an uncertain and chaotic future (Mammri, 2011). Regarding the consequent urban visual attributes, they are influenced by the spatial disposition of urban sprawl indicators, noticeable fragmentation, and uneven urban landscapes (Osman *et al.*, 2016). Previous studies on the city of Batna have primarily addressed specific aspects of the urban fabric, such as morphological analyses or investigations at the neighborhood scale (Bendib and Naceur, 2018; Touati and Arrouf, 2024). In contrast, the present study adopts a more integrated perspective, examining the city as a whole. Within this comprehensive approach, particular attention is given to urban RN in particular, Pedestrian-friendly streets (Ayman AbdelAziz *et al.*, 2020). These networks constitute essential and widespread components of the cityscape, manifesting through diverse visual configurations, embodying the fundamental principles of planning (Biljecki and Chow, 2022; Chen *et al.*, 2024). The usage of these spaces by individuals shapes the trajectory of the UG.

Moreover, the issue of human interaction cannot be discussed without discussing pedestrian movement and experience (Wang *et al.*, 2023; Yassin, 2019). Furthermore, the dual role of the street, both unifying and segmenting (Sutcliffe and Cipkar, 2022), illustrates the capacity of Mediterranean cities to encourage social interactions and cultural exchanges through accessible public spaces, while revealing the vulnerability to social fragmentation and spatial segregation in the event of unbalanced urban development. For several decades, they have constituted a privileged tool in the production of cities. Extending from streets to neighborhoods, the QUS experienced by these urban dwellers at this level will determine the future of the PUS. The Sinjar city study (Omar *et al.*, 2022) makes a relevant contribution to sustainable urban planning in the southern Mediterranean context, mobilizing GIS capabilities to guide the city's UG (Shojaeivand, 2019). However, integrating the structure of the RN would have strengthened the approach, taking into account mobility dynamics and spatial connectivity. A hierarchical and thoughtful RN is indeed an essential lever in a long-term sustainable development vision, facilitating accessibility, limiting uncontrolled sprawl, and structuring centralities. In another perspective oriented mainly on technological performances in generic urban environments, the study of (Al-Neami *et al.*, 2025) addressed reflections on connectivity without explicit analysis of spatial organization or UC. The adopted approach in this paper makes it possible to understand the PUS in relation to the QUS and the road structure, providing a relevant spatial framework for the implementation of technological solutions such as the intelligent reflecting surfaces, by integrating the physical and morphological constraints of urban space into these reflections. In his article, (ADIO *et al.*, 2024) discussed current trends in digital urban planning by referencing various international case studies, such as Singapore, Songdo, Toronto. This analysis facilitated an understanding of the factors contributing to the successful implementation of smart cities across diverse contexts. The article provided specific examples of how technology is integrated into urban planning, particularly at the RN scale. However, it did not offer a structural reading of urban space. The study of (Kaled and Maysoon, 2024) proposed a descriptive and analytical methodology aimed at exploring the visual and aesthetic

determinants in the design of public spaces in Arab cities. Unlike this study, where space syntax is used to support a visual and symbolic reading, this paper's approach focuses on the topological structure of the urban RN, measuring accessibility, connectivity, depth, and integration of axes. It is based on rigorous mathematical modeling and provides quantifiable results. Several other studies have contributed to objectifying elements that were previously difficult to measure, such as atmosphere, movement, and perception of urban space, by extending beyond classic qualitative methodologies; in line with the studies conducted by Li (2024), Ma *et al.* (2021), and Zhang *et al.* (2018, 2019). Whereas these studies emphasized perceived formal QUS through street images. In comparison, this paper proposes a functional and dynamic approach by analyzing the structural performance of the spatial network, using space syntax measures. The two approaches are thus complementary; one sheds light on the visible and sensitive QUS, the other on the underlying structure and the potential for use. To plan for the future, the current production of cities must be rethought through analyzing the UR. The spatial layout of the Algerian cities reflects the human experiences, different indicators about the uniqueness, and it can also talk about the future of the city. Certainly, it can indicate whether the city is developing qualitatively or not (IPHS, 2016).

QUS through road network analysis

Cities have a rich tradition of aiming for perfection, but they fail to achieve this goal (Oliveira, 2022; Robertson and Neuhaus, 2024). When talking about the UG and the production of a QUS, this concept should be defined. (ISO) Standards define it as the capability to meet stated or implicit requirements (El Sharnouby, 2019). QUS is a frequently used but it is vague term in the urban context. It is a fundamental component of political and societal issues (Castel *et al.*, 2019; Golshan *et al.*, 2021). This concept has progressed alongside inhabitant life, for this reason, researchers suggested examining the urban environment primarily in terms of people, the human senses and bodily movement, since individuals interact with the living environment and travel through it through senses and actions (Daniel and Vining, 1983; Gehl and Svarre, 2013; Kanelli *et al.*, 2021; Krzeptowska-Moszkowicz *et*

al., 2023; Monteiro and Pinho, 2022; Stahl, 2009). Due to the omnipresent subjectivity in this field (Adams, 2013; CAUE *et al.*, 2014; MERAD, 2017), it remains multidimensional and complex to assess, and requires several criteria for comprehensive assessment. Hence, this work is important as it aims to present these various theoretical notions for interpreting the topics of quality and spatial development, utilizing MQI. Gehl defined twelve criteria of quality, serving as guidelines for designing urban spaces, organized into three main categories: « Protection, Comfort, and Enjoyment » (Gehl and Svarre, 2013), which align the different measures of SST, because the perception of these criteria is influenced by the accessibility, visibility and centrality of spaces, and also, a fundamental aspect of the SST is to examine the visual perception of city users through these dimensions (accessibility, centrality and connectivity). Therefore, these categories are influenced by the parameters of space syntax. Within urban life, quality is experienced through the living conditions and the urban landscape, while in society, it is related to aesthetics and the symbolic charge of buildings (Ben mehni and Amokrane, 2020; CAUE *et al.*, 2014; islami *et al.*, 2017). A city's quality depends fundamentally on both physical and social elements. They share a dependency relationship, where one affects the other and vice versa (Attig, 2019). Although people may recognize urban quality when they see the output of a city, sense ambient environmental quality, prompting planning tools to prioritize visual impact (Ervin and Steinitz, 2003), because visibility plays a crucial factor in influencing movement and choice of trajectories of city users (Varoudis, 2014), and because visual satisfaction is the most common need among human beings (Mebirouk, 2002). This fact brings up the question of consultation with residents and the move from top-down to bottom-up approaches and strategies (Musango *et al.*, 2017). Enhancing the image of the city cannot be achieved without the continual contribution of the population (Ben mehni and Amokrane, 2020; Hunziker *et al.*, 2007; Weitkamp *et al.*, 2007).

Understanding the UC through Space Syntax Analysis: Indicators provided by Depthmap

The study used Depthmap, which is a piece of software, as defined by Bill Hillier. In the late 1970s and early 1980s, Bill Hillier and his colleagues at the

Bartlett School of Architecture at University College London introduced SST for studying, examining, and analyzing spatial relationships (Van Nes and Yamu, 2021). It is one of the tools which offers a concise definition of urban space, able to detect subtle local structures that seem almost non-existent (Hillier *et al.*, 2012), able to capture the urban structure's skeleton (Porta *et al.*, 2006) and it provides the synergy between number of properties in a syntactical way within the space, without analyzing the place character (Van Nes, 2014). According to Bill Hillier's theory, the city consists of two sub-systems; the first is the physical one made up of buildings connected by the street pattern, and the second sub-system apprehends human movements, interactions, and activities (Attig, 2019; Xia, 2013). The two interact over time, this space-society paradigm has direct implications for PUS and QUS in the broader sense (Karimi, 2018). SSA presents MQI (Han, 2009). This topological mode abstracts urban space by discarding geometric properties such as location, length, and orientation; thereby simplifying patterns and relationships in urban space into a mathematical model (Attig, 2019; Ma *et al.*, 2019). It captures the diversity of urban forms, even if they are part of a complex relationship system, highlighting that the way UG is structured has a direct impact on the QUS (Al_Sayed *et al.*, 2014). Several space syntax techniques allow analyzing the visibility and perception of urban space at different scales, combining several complementary approaches (Askarizad *et al.*, 2024). One example is isovist analysis, which measures fields of vision from a given point, revealing what an individual can see from a fixed position. Visual Graph Analysis (VGA) extends this logic to an entire space by mapping the continuity of visual fields across a network. Axial Analysis traces all possible lines of visibility and movement in space, allowing for to assessment of the overall connectivity and accessibility of the urban fabric. Finally, agent-based modeling simulates the movements of pedestrians or users in this space, integrating visual and behavioral biases. Together, these methods offer a detailed reading of urban visibility, ranging from the local perspective to large-scale spatial organization (Van Nes and Yamu, 2021). In this research, axial analysis was favored because it allows a global reading of the spatial structure of the city. Applied to the entire city of Batna, this method highlights the structuring axes, the zones of centrality, as well as the

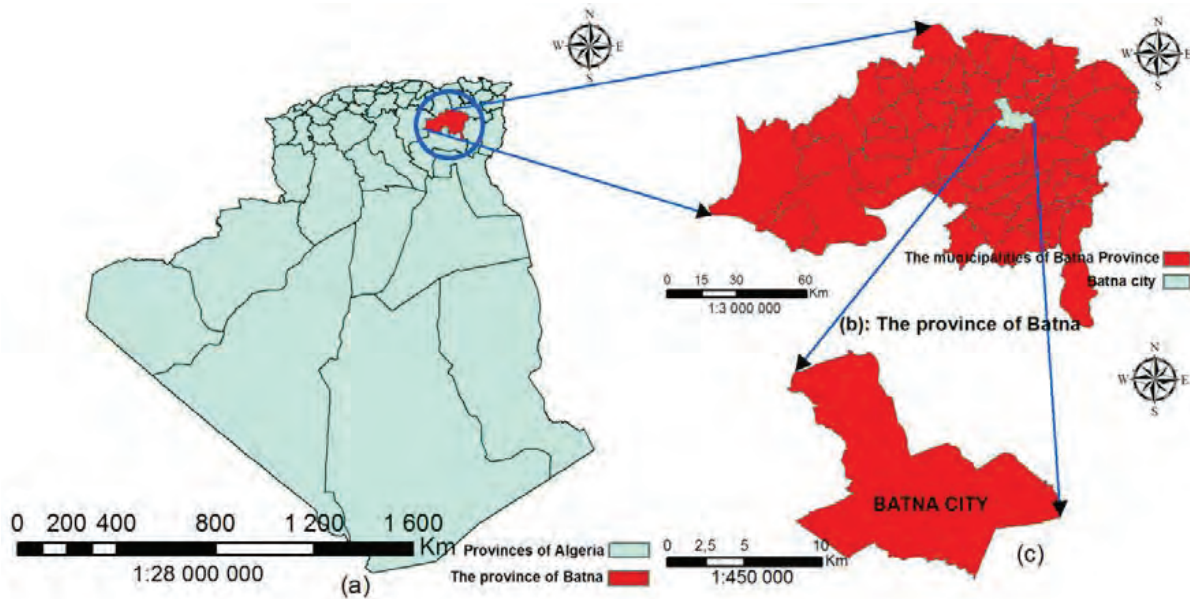


Fig. 1: Geographic location of the study area:(a) The location of the province of BATNA in Algeria, (b)The province of Batna, (c) Batna City. Source: The authors

enclosed spaces, thus providing a solid basis for the interpretation of urban users' perception, UG and the QUS of Batna city.

MATERIALS AND METHODS

Research area

The commune of Batna is the administrative center of the wilaya that has the same name, located in the North-East of Algeria Fig. 1. The urban area of Batna is characterized by a flat landscape, surrounded by mountains. These constraints deliberately limit the spread of urbanization. Therefore, topography has always played a key role in choosing city locations and shaping the UG for several purposes. Due to the geographical location and the rich historical background, Batna city attracts visitors from the surrounding communes and regions. It includes a large industrial zone, a major university center, and two major hospitals. This grants it a strategic location and a social hub for the development of several sectors. Additionally, it stands out as an economic center. This attractiveness led to a demographic growth, generated also an accelerated urbanization and the emergence of new residential areas (Hamla 1, 2, and 3), shown in Fig. 2. Simultaneously, the demand for urban mobility is also rapidly increasing, resulting an

urban development pattern that deviated from the original European model to a city in transition toward modernity with limited availability of public spaces.

Data collection and approach methodology

To understand the urban complexity, the logic of the production, and the evolution of this city. The study proposed a methodology that combined «the empirical and theoretical orientations» (Swaffield, 1991). The theoretical sections have explained the concepts related to urban form, growth, inhabitants' perception, and the scale of intervention. Empirically, to collect quantitative and qualitative data, this methodological approach combined a spatial analysis based on the main parameters of space syntax and the questionnaire survey. Site observation, OpenStreetMap (OSM) files, the PDAU (Master Plan for Development and Urban Planning; an urban planning instrument known in Algeria by the French name 'Plan Directeur d'Aménagement et d'Urbanisme'), and, in particular, the POS (Land Use Plan) (Bendib and Naceur, 2018) of Batna city have been used to provide reliable and relevant spatial inputs Fig. 3. The DXF file was processed to eliminate irrelevant details, preserving only the crucial existing spatial features like roads, pedestrian paths. Once again, it

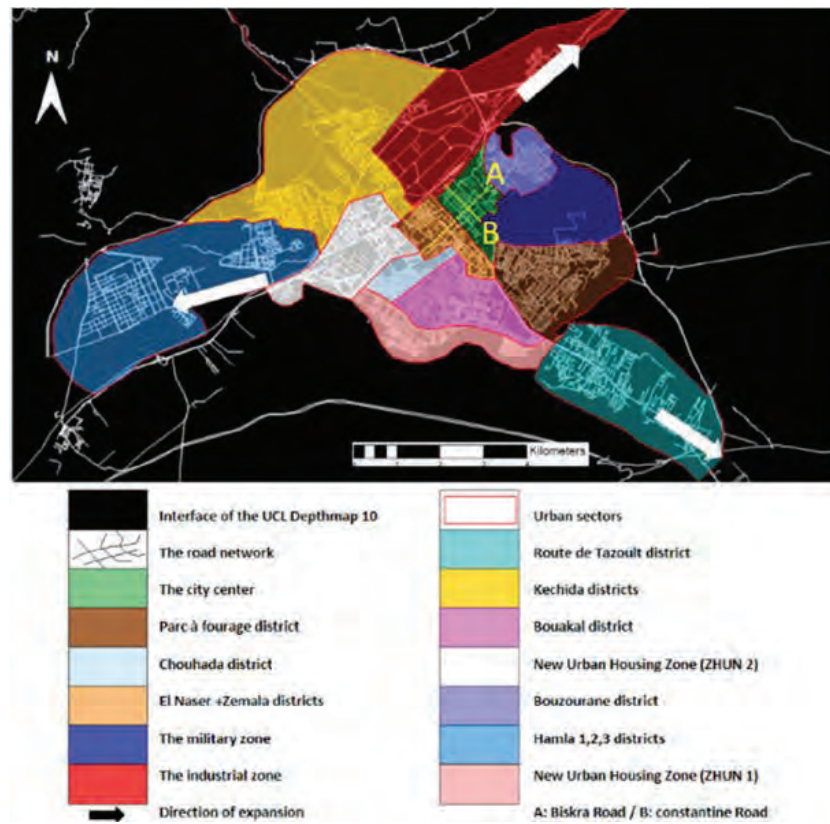


Fig. 2: Urban sectors of Batna City. Source: The authors

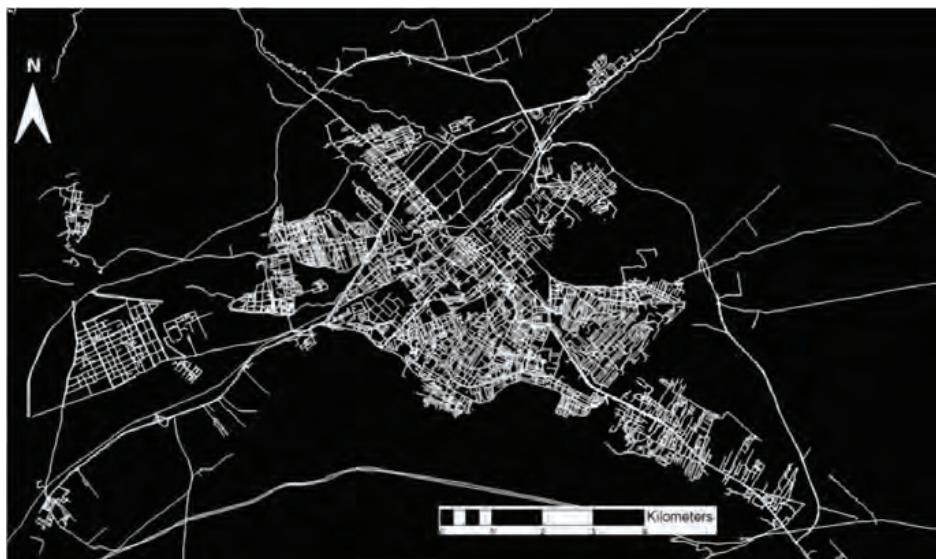


Fig. 3: Batna natural city, the unanalyzed spatial configuration (Dxf file opened on UCL Depthmap 10 -input). Source: The authors

was validated using satellite imagery (such as OSM) and field observations to ensure the spatial accuracy and completeness. The analysis extracted three key parameters (Connectivity, Integration, and Entropy); subsequently, the results were obtained by the analysis of several maps and the perfect knowledge of the study area. As residents and users of this city, this research relied on direct personal observations of the urban space under study. These observations, derived from daily experience and fieldwork, enriched the analysis and constituted a starting point for in-depth reflection on the spatial dynamics that characterize the city, enabling a more accurate and realistic understanding of the transformations taking place within the city. Research conducted in previous studies has uncovered a substantial variety of viewpoints and perspectives regarding the relationship between spatial configuration and social dynamics in urban spaces (Askarizad *et al.*, 2024). Several of these studies (Baiz and Atakara, 2023; Mojaveri *et al.*, 2022; Zhang *et al.*, 2023) have advocated for the implementation of a questionnaire, as external data to explore other dimensions of cities (such as societal processes, human behavior, socioeconomic and environmental factors). The researchers used the questionnaire and observations to interpret the topological results obtained by space syntax, to study the contexts of different cities in Iraq, Iran, and China. And this constituted a limitation to the use of the Space Syntax tool. Consequently, this study employed a social survey, through the questionnaire, which had been administered to 390 persons who had often lived or visited the city of Batna in 2024, including questions on the interaction with the urban space and the transition from a low to a high urban density. It was designed as a complementary tool to examine forms of public space appropriation and Road network usage, to evaluate the perception of urban dwellers about the living space, and to allow the comparison between different areas, specifically, through questions related to the frequency of users' movement. Three selected questions were included to complement SSA findings. To enhance analytical rigor, the study incorporated statistical methods, executed using SPSS software. It examined the relationships between key spatial parameters through Pearson and Spearman correlation tests, as well as ANOVA derived from a linear regression test. Two dualities were analyzed: connectivity/ integration and connectivity/

entropy. These statistical tests aimed to reveal the strength and nature of correlations, thus providing a thorough understanding of spatial dynamics and their perceptual implications.

The city of Batna shows irregular urban networks Fig. 3, where the districts have spontaneously evolved. Neighborhoods have undergone multiple additions, modifications, and redevelopments based on various elements: Social interactions, economic issues, cultural influences, and political contexts. The observation that the informal sector predominates despite large-scale urban expansion in the city of Batna raises fundamental questions about urban dynamics, development mechanisms, and the resulting city image. An accelerated decomposition of urban morphology has been observed, generating small centralities in the process of being constituted, creating complementary relationships that do not exclude the individuality of each urban entity, and without diluting the structural and functional importance of the city (Kumps *et al.*, 1984). The map (Fig. 3) shows a “**connected matrix**” (UN-Habitat, 2018) of streets that are public spaces, which form the basic framework and public space infrastructure of Batna city, upon which the built environment rests and urban dwellers execute various activities.

Analytical framework

a. The axial map

It is the primary representation to analyze urban forms as a spatial configuration, the key element of the modeling technique, and the main model produced by Space Syntax software (Hillier and Chiaradia, 2004). It consists of the representation of the urban road network (where the smallest possible number of straight lines are drawn that cross the accessible spaces of a city). It was initially formulated based on visibility and accessibility's perspective (Han, 2009); the original design of the axial map is based on the principle that urban spaces are arranged according to what people can observe and easily access. In other words, the more visible and easily accessible a space is, the more likely it is that that space will be frequented. This links visual perception to how the space is used and occupied. Therefore, these axial lines are interconnected and accessible (Hillier and Chiaradia, 2004), represent directions of unblocked movement and visibility (Han, 2009). It is then analyzed using topology and mathematical

graph theory. Topological analysis examines how different axial lines are connected. The aim is to understand the structure of the network abstractly, without considering exact distances or angles, but focusing on the relationships of connection and continuity between spaces. Graph theory then makes it possible to determine several essential quantitative measures. Based on the above, the axial map of Batna city's urban grid was presented and analyzed configurationally.

b. Axial analysis

This research has calculated space syntax attributes numerically and graphically by utilizing UCL Depthmap 10 software, generating an axial map for the whole of Batna city. This map, Fig.3, is built based on an accurate, scaled, and updated electronic cadastral plan. The axial map is created for the study area, covering an area of 116.41 km². The input data (the map imported into UCL Depthmap) must be in DXF format Fig.3, which consists of lines representing the road network across the entire Batna city. Overlaying the resulting graphs with the input map (Fig.3) then allows for verification of the validity and accuracy of the generated graphs. The base map imported (the DXF file) was converted into an axial map using "Map" options in the software, generating a network of the longest and shortest straight lines covering all accessible and visible spaces of Batna City. After constructing the axial map, a graph analysis was performed, which calculates the three syntactic measures. To achieve significant results, the study configured the analysis to include multiple Radii, betweenness measurement, local and length-weighted measurements of the lines (This is a programming of the parameters that appear in the command window), which indicate an analysis focused on both local measurement and the importance of the lines in the global network. To run the graph analysis, local and global topological radius (R) (n, 2, 3, 5, 7) have been selected: This means that the analysis has considered elements located from two "steps" away from each element analyzed up to a larger scale, to cover greater distances and capture a more global perspective of the urban network. Therefore, these radii are used to analyze local depth within walkable urban areas and to observe vehicle movements across the city of Batna. This technique takes into consideration the visual perception of

pedestrians and people in vehicles. After running the graph analysis, the software generates a range of spatial metrics. Among these, the selected three parameters. Connectivity, Integration, and Entropy are spatial attributes that explain functional patterns of land utilization, the vehicle and pedestrian movement flows, aspects of social welfare, and discontent within Batna city. In conducting the SSA, the study reveals methodological limitations inherent in this research. The Axial Analysis is limited to modeling the road network in the form of straight lines representing the longest visual axes, which reduces the spatial complexity of the city by neglecting buildings, height variations, and the three-dimensional dimensions of the urban environment. This is the case of several studies which have used the same software, either for an architectural or urban analysis (Chen, 2022; Ravari et al., 2024)

RESULTS AND DISCUSSION

Initially, Maps generated by space syntax confirm the idea that geometric order is difficult to identify because urban spaces have adapted to local needs, natural features (such as landforms), and particular historical developments, instead of conforming to the PDAU. In terms of the line length distributions, across all scales ranging from the neighborhood to the whole city, the axial map is made up of a minimal quantity of long lines alongside a vast multitude of shorter ones (Hillier, 2009). Significant differences have been found between sub-areas (The city center and the adjacent neighborhoods); the city core and the new contemporary sub-area (Hamla neighborhood + La route de Tazoult) (Refer to Fig.2 which contains the names of the city's districts), exhibited higher levels of spatial connectivity, Integration, Mean depth, Node count, choice and the lowest level of Entropy, as shown in the figures Figs. 4, 5, 6, 7, and 8. These space syntax attributes have been linked to several aspects of people's behavior and perception in space. An example, the most integrated spaces are places of intense urban life. Furthermore, it was observed that the regular road network has the strongest influence on pedestrian movement. Whereas, in the recently created and evolving sub-systems, the physical dimension has the strongest influence on pedestrian movement. Also, the level of road network integration influences the location of commercial activities; there is a significant correlation between topological



Fig. 4: Arbitrary section of the Axial map of Batna_Choice. Source: The authors

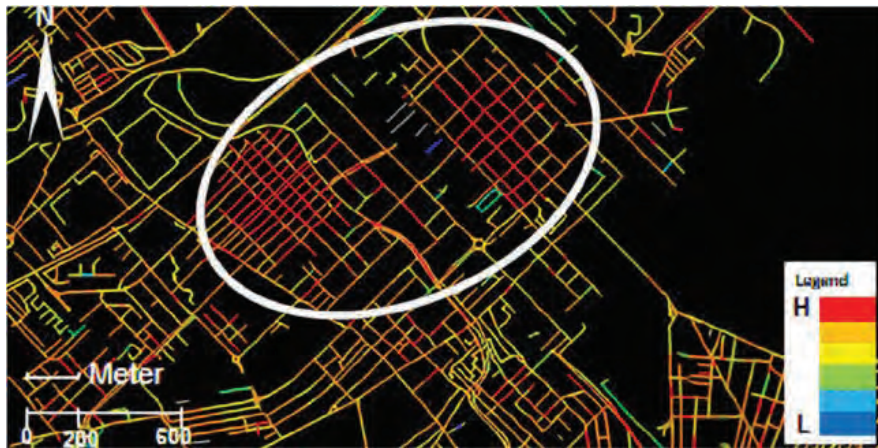


Fig. 5: Arbitrary section of the Axial map of Batna_Mean depth-R2. Source: The authors

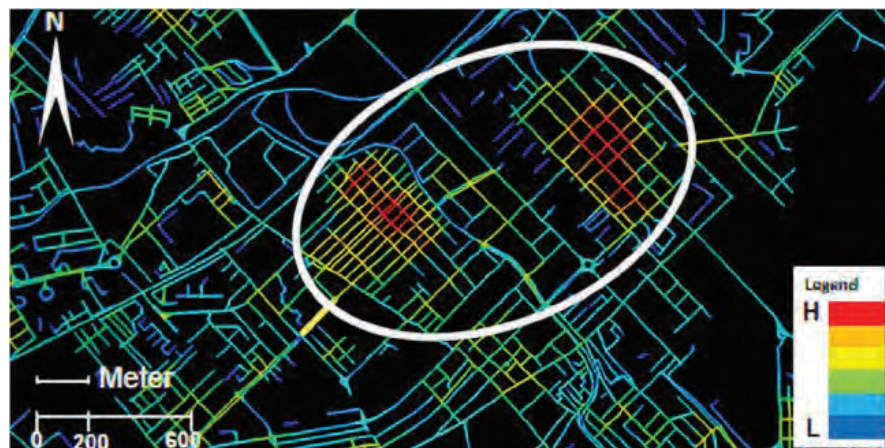


Fig. 6: Arbitrary section of the Axial map of Batna_Node count-R2. Source: The authors

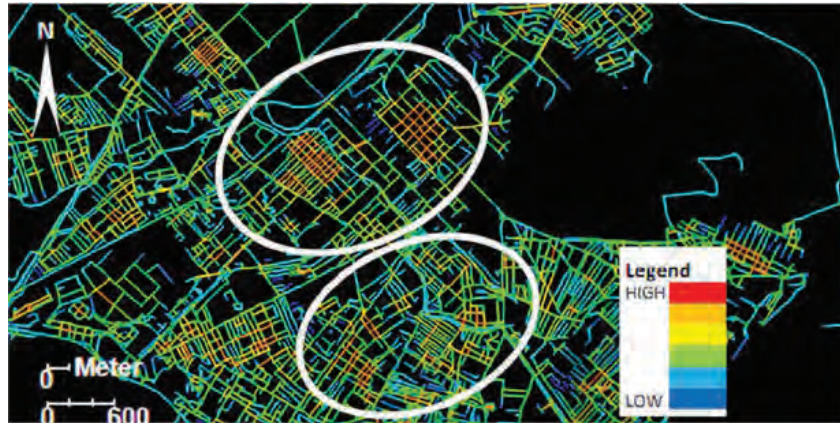


Fig. 7: Arbitrary sections of the Axial map of Batna_Connectivity-R2. Source: The authors



Fig. 8: Route de Tazoult district_Connectivity. Source: The authors

metrics and human movement rates, and individual spaces can be ranked based on these metrics to predict urban users' movement (Jiang, 2009). The great veins of our cities (the road to Biskra and the road to Constantine) extended from the core to the sub-areas. These wide streets that constitute the main traffic network are highly integrated, with high connectivity value. These roads are central spaces in this spatial network, which were once designed to promote a balance between the different modes of transport. However, over time, these urban arteries have become spaces dominated by automobiles. The priority given to motor vehicles has often led to the neglect of pedestrians and other forms of transport. Sidewalks are reduced, pedestrian crossings are insufficient, and public spaces are transformed into

simple passageways for cars. This preeminence of the automobile over Batnian's old urban infrastructures profoundly changes the character and functionality of these once lively and accessible spaces, especially at the side of the city entrances, although this does not change the characteristics of these streets in the heart of the city. Detectable by Batna city's users, these characteristics deliberately help to neutralize urbanization expansion and determine its direction and shape through concentration or dispersion. The social value of streets makes them significant within the whole city.

The higher levels are graphically expressed through the continuity of lines, meaning lines connected by almost straight lines. This occurs at different scales, and at each scale, the lines are locally longer. The

absence of a regular and geometric pattern, with the presence of long lines, is actually due to the presence of fallow lands and undeveloped plots. Batna city undergoes linear urbanization along the two main roads that constitute the principal transport axes, and acquires a dual structure through the geometry and scaling of the street networks: a dominant organic layout in the foreground, characterized by shorter lines and less linear continuity, and another more regular network, especially in the city center.

Connectivity

It is a static local measurement and the most obvious parameter for topological analysis. The connectivity graph is composed of axial lines that represent continuous visual axes and circulation axes. This local metric considers all direct links each street has with nearby and adjacent streets. A street that connects to numerous side streets exhibits a high level of connectivity, while a street with limited connections shows a low level of connectivity. These values are illustrated using a range of colours. The linear spaces or the street structure are considered as a spatial configuration, which describes human behavior and activities. The colorful representation facilitates the analysis of local dynamics and allows urban planners to quickly identify the most interconnected roads within an axial map. This definition aligns with the findings of (Dong et al., 2022) about urban vitality, which is seen as a key component of the QUS and

PUS, and it is reflected through external spatial features, functional characteristics, accessibility, and location, activity, and diversity experienced within a given urban space, and visitors' perceptions. This view is supported by Mohamad and Said (2014), who have recognized that the quality of street connectivity is a key element in enhancing the QUS. Unlike global metrics such as integration that examine the whole urban network, connectivity is referred to as a local metric since it focuses solely on interactions within a limited area of a street. It is also static, because it does not change depending on other parts of the urban network. It focuses only on the number of immediate intersections of a street with its neighbors (Attig, 2019; Van Nes and Yamu, 2021). The degree of connectivity for each street in the city of Batna is visualised on a map in Fig.9.

The most connected segments (5-7) are rare; less than 10%. Segments with connectivity 2 constitute the majority, 53.8%, reflecting a fragmented urban structure (see Fig.10). As a static local metric, connectivity subtly indicates how close the urban blocks are along axial lines. The layout of the main roads influences the directions of the plots, which tend to bend in response to the influence of these highly connected axes. The high connectivity is registered in several districts, whether formal or informal, but especially in formal ones, such as the city centre (centre ville, stand). Here, streets have many connections to the side streets and have a high



Fig. 9: Axial map_ Connectivity (Generated using UCL Depthmap 10 -Output). Source: The authors

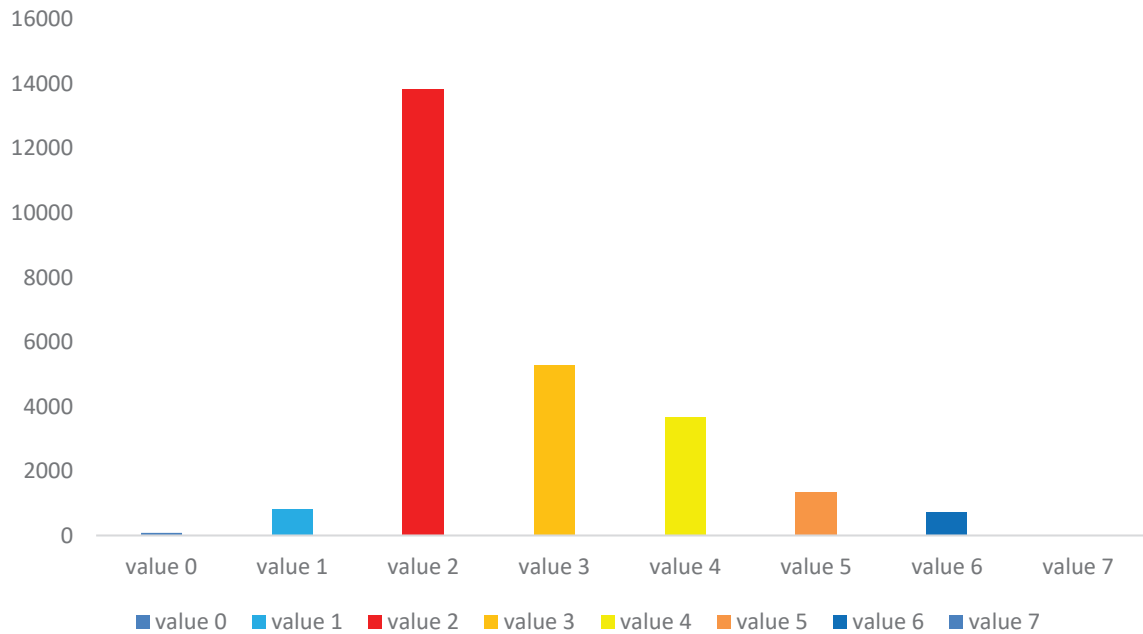


Fig. 10: Histogram explaining the measurement of connectivity in Batna city. Source: The authors

connectivity value, as visualized in the colour range (the red and yellow (on maps) are roads with the most connections to adjacent roads). Whereas, the value goes down heading to the extension areas of the city, to large arborescent systems (Route de Tazoult, Kéchida). Consequently, streets in these districts with a few connections have a low connectivity value, displaying also the range from public to private spaces in the Batna Road network. The extension areas of the city have sizably reduced allocations of land for public spaces. Some people may be excluded from informal spaces if they feel unsafe. The UC of Batna city and the street atmospheres, at this scale, highlight the growing importance given to interactions between humans and the urban setting, notably by the need for the strong return of pedestrian spaces, to enhance the QUS. This desired transformation towards more accessible agglomerations, especially at the entrances and exits of the city of Batna, underlines the importance of rethinking the PUS to better meet the expectations of users. The urban atmosphere is perceived as something tangible of the UR that materializes through space and users, shaping sensations, behaviors, and interactions, as reflected in the layout of roads and dwellings.

Integration

As defined by Hillier and Hanson (1984), within a configuration, Integration represents a normalized form of the typological distance between a particular space and all other spaces in the system (Hillier *et al.*, 2012). This measure assesses the potential of a segment as a destination for movement (Hillier, 2009). It symbolizes the level of depth and shallowness within an urban system, in which highly integrated regions have been shown to attract movement and activity (Alalouch *et al.*, 2019). Up to the specified radius and specified distance definition, configurational measures R2 to R3 are considered local measurements, while measurements R5 to R7 are global measurements. Integration is often associated with a linear increase in mobility and movement, and is also called accessibility in this context (Hillier and Chiaradia, 2004).

The graphical interface highlights Batna's urban spaces through 25753 axial lines analyzed, colored uniformly according to the level of local spatial integration, allowing a detailed assessment of spatial integration across the city. The red segments represent the areas that are the most easily accessible topologically, while the blue symbolizes the most

distant lines, Figs. 11 and 12. Fig.11 shows the same analysis with the analytical radius limited to a depth of two. The calculation considers immediate and localized structure, calculating for each line of the axial map all the directly connected lines, as well as those subsequently connected to them. This measure is called the “local” spatial integration map R2 or “local” spatial accessibility, identifying the development of secondary urban centralities in Batna. Fig.12 shows

the spatial integration map R7. The results obtained when using a local radius R2 in the integration calculations are the most significant. The majority of axial lines have a relatively moderate degree of integration, with an average value of 1.17. This indicates that, in general, the city has a certain level of accessibility, but no place is perfectly integrated. The maximum value is 2.63, shown on the map by the red dispersed areas. The dispersion of these areas on

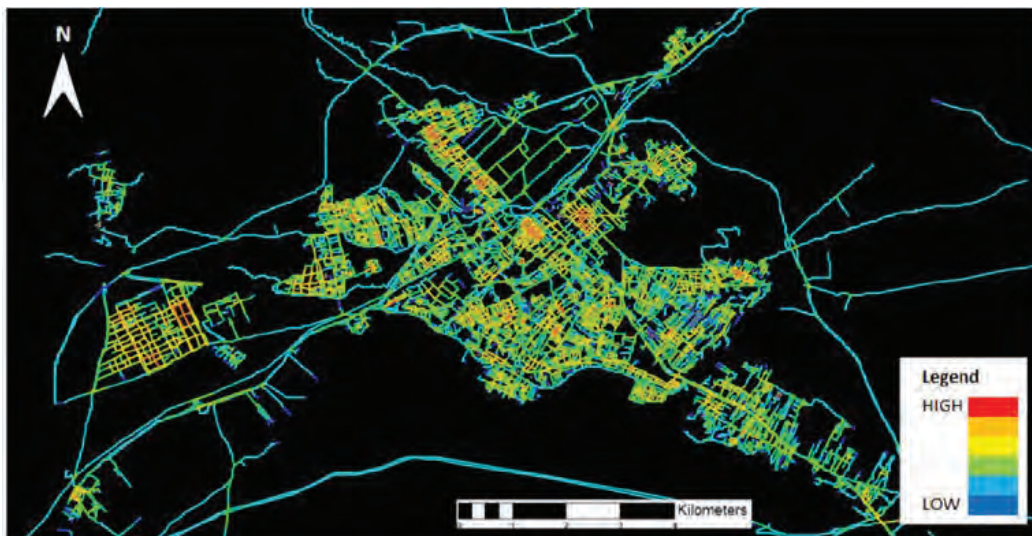


Fig. 11: Axial Analysis_ Integration Radius 2, (UCL Depthmap 10 Output)- Source: The authors

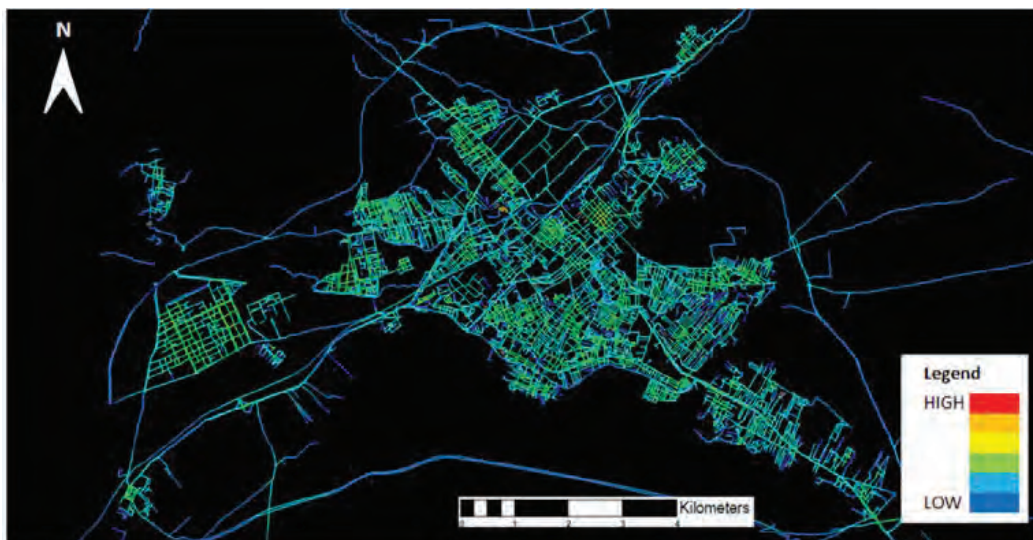


Fig. 12: Axial Analysis_ Integration Radius 7, (UCL Depthmap 10 Output)- Source: The authors

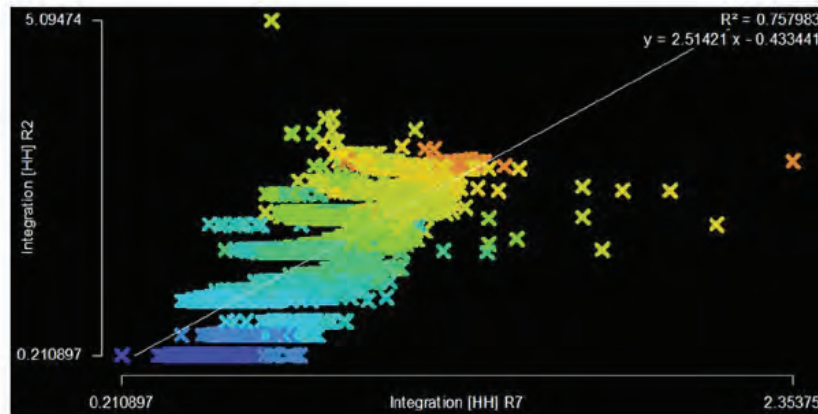


Fig. 13: A graph representing the correlation between Integration R7 (X axis) and Integration R2 (Y axis). Source: The authors

the map, rather than being concentrated in a single space, indicates a heterogeneous distribution of accessibility in the city. Some points of the city have an efficient spatial integration, but being far from each other indicates a polycentric urban structure. This result indicates that there are several centers of activity in the city (the city center, the industrial zone of Kechida, the new urban pole of Hamla), and each space is well connected to the immediate surroundings. Extremely isolated areas or streets in the urban network are presented by a minimum value of 0.21, indicating poorly integrated axial lines. The axial lines demonstrate considerable diversity in terms of accessibility and integration within Batna's urban network; this is evidenced by a standard deviation value of 0.39, reflecting significant variation in the spatial characteristics. To further explore the relationship between these two topological integration scales, a scatter plot was generated using UCL Depthmap software Fig.13, integration R7 (x-axis), representing a global scale, and integration R2 (y-axis), associated with a local scale. The resulting graph highlights a strong positive correlation, illustrated by a coefficient of determination $R^2 = 0.75$. This means that 75% of the variance of the integration values R2 can be explained by the variance of the integration values R7, according to a linear relationship. In other words, the most integrated segments at large scale (R7) are also, to a large extent, at a smaller scale (R2), suggesting a structural synergy between the two levels of topological analysis.

These radii, R2 and R7, allowed for analyzing

localized areas in an urban network to understand the immediate accessibility and the local centrality. This matches the findings of prior research by Liu *et al.*, (2021), who proposed examining the quality and vitality of the city through internal indicators, specifically "small-scale urban public street area". Also, they helped to identify proximity centers or sub-spaces within a larger network. This allowed revealing which neighborhoods have good connectivity with the immediate surroundings, taking into account the entire city network. Highly integrated areas are key points of centrality and connection, facilitating movement and concentrating traffic flows. The absence of uniformly red sections implies that there is potential for the city to improve connectivity and accessibility within various parts of the urban framework. The notable variations in integration values indicate considerable disparities in the connections between various districts and streets of Batna city, which may influence mobility and access to services throughout Batna. Results of the survey about the most frequented areas support (Hillier and Hanson, 1984) findings and the findings of the present study regarding spatial integration and connectivity as attributes defining the QUS. It confirms that the PUS, in particular public spaces, influences social behaviors and interactions. This dynamic contributes to the improvement of the QUS and is important for planning UG. The spaces identified as the most frequented in the questionnaire are also those that have a strong interconnection with other spaces. These spaces are accessible and welcoming to all city

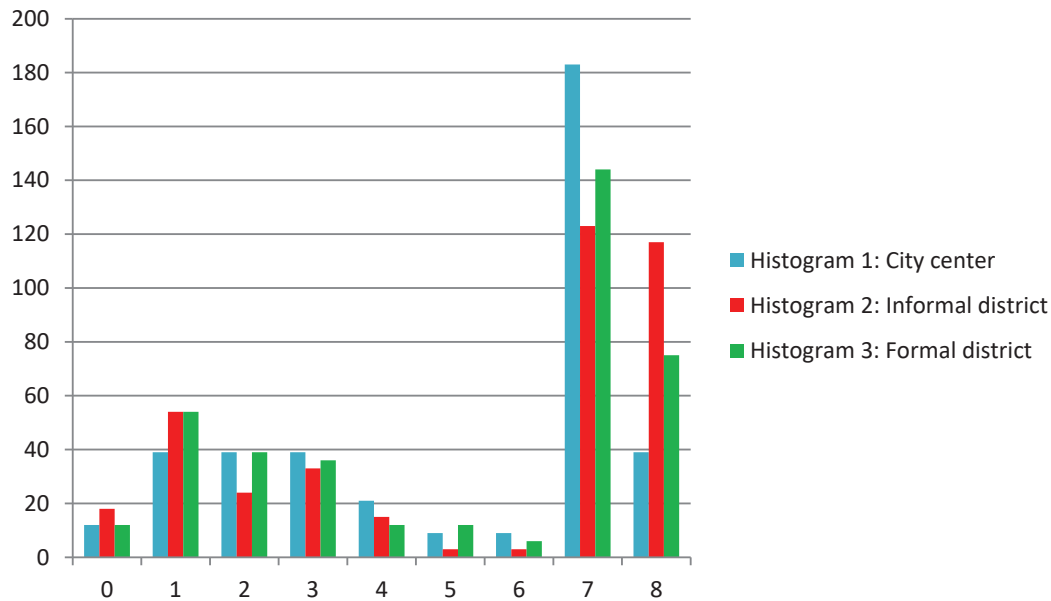


Fig. 14: A combination chart of histograms representing the frequency of visits to Batna city's center, to an informal neighborhood, and to a formal neighborhood. Source: The authors

users, also defining safe spaces. Spatial connectivity and integration play a critical role in attracting movement and activity in a given urban environment.

The new centralities are better represented by local measurements. While the spatial configuration R7 exhibits some homogeneity. This measurement provides more detailed information than the overall view. It gives an image of all the winding, often radial roads that every Batnian knows, which are often the best roads for most destinations. The city center districts, certain informal neighborhoods (Kéchida), and the new urban extension Hamla remain dominant. The city center, stand, chikhi, and Hamla districts are integrated at the level of a global measure and also present very powerful local integrators. Histogram (1) Fig.14: represents the frequency of visits to the city center of Batna city by 378/390 respondents. The horizontal x-axis shows the number of visits to the city center per week, ranging from 0 to 8. The number 0 represents the fact that the person the questioned has never visited the city center. The number 8 corresponds to answers indicating that the person lives in the same neighbourhood or works there every day. The number 7 represents a reference, taking into account the number of days of the week, and setting the number 7 times/week as

the response, indicating the maximum attendance in the city center of Batna. The vertical y-axis represents the number of respondents corresponding to each frequency of visits. The same principle is used to analyze the other two histograms. The majority of respondents (46.9%) visit the city center daily (7 visits per week (7/7)), represented by the largest bar (about 183 respondents). 0 to 3 visits per week represents a rate of 30%. About 5% of respondents visit between 5 and 6 times a week, and the other respondents chose answer 8 (representing a rate of 10%). The analysis revealed that the city center is a central location for respondents, with almost half visiting it every day. The remaining visitors come mainly 1-3 times a week. The histogram (2), Fig.14, represents the frequency of visits to an informal neighborhood. The analysis is based on a sample of 390 respondents, and the study received 372 responses to this question. The histogram shows 3 types of attendance: 1- despite the informal nature of the neighborhood, 123 of respondents (31.5 %) frequent the informal settlement every day of the week. It remains a place frequented daily by a third of respondents, due to professional and residential activities. Response case (8) represents 30% of respondents, or 117 people, who selected this answer. These respondents

Table 1: Correlation Analysis Between Connectivity and global Integration in Batna city

		Connectivity	Integration [HH] R2
Connectivity	Pearson Correlation	1	0.375**
	Sig. (2-tailed)		0.000
	N	25753	25753
Integration [HH] R2	Pearson Correlation	0.375**	1
	Sig. (2-tailed)	0.000	
	N	25753	25753

** . Correlation is significant at the 0.01 level (2-tailed).

probably live or work in the informal neighborhood and go there daily. These high percentages show that the informal settlement is a living space for a significant part of the population, and it is not just a place of passage. Moderate frequency, which is represented by a percentage of 13.8% (1/7), 6.2% (2/7), 8.5% (3/7), and 3.8% (4/7): these percentages are relatively significant, often linked to semi-regular activities and do not require daily presence on this type of urban fabric. The low percentages represent frequencies of (5/7 and 6/7), indicating that this type of organic urban fabric is a place of passage. The histogram (3), Fig.14, represents the frequency of visits to a formal neighborhood. The analysis is based on a sample of 390 respondents, but the study received 378 responses to this question. 144 Respondents frequent a formal neighborhood daily (7/7), or 36.9%. This indicates that a large percentage of the questioned people are in contact with the formal neighborhood every day. This has resulted from the strong presence of important activities and residences in this urban area. 13.8% of respondents only visit the area once a week. This suggests that some urban users only need to go there for specific reasons. 10% and 9.2% representing respectively 2/7 and 3/7 frequency, indicate that the presence in this type of neighborhood varies according to individual needs. Two low percentages, 1.6% and 3.1% representing respectively (6/7, 4 and 5/7) frequencies. 19.2% of respondents chose index 8; in the case of the formal neighborhood, these respondents live or work in the formal districts of Batna city. These results reveal a difference in the use of formal neighborhoods. This daily or occasional visit depends on people's needs. The city center is the most regularly visited zone, with 46.9% of respondents visiting it every day of the week. In formal residential areas, 36.9% of surveyed people attend daily, indicating a considerable amount, yet it is still lower compared to the city center. Among

respondents in informal neighborhoods, 31.5% report visiting daily, highlighting that these spaces are active living areas. These results confirm that Batna's urban core influences perceptions of the entire urban space.

Relational forces in spatial configuration: the case of connectivity and integration

In order to evaluate the strength and characteristics of the relationship between Connectivity and spatial Integration R2, both Pearson's correlation coefficient and Spearman's rank correlation coefficient were calculated (De Lotto *et al.*, 2024). Pearson's test assesses linear dependence based on the assumption of normality, whereas Spearman's test identifies monotonic relationships without the necessity of a normal distribution. The agreement of findings from both statistical methods reinforces the reliability of the observed correlation.

-The correlation analysis (Table 1) conducted in SPSS between Connectivity and Integration R2 aims to understand the extent to which local structure (immediate connectivity) influences and it is associated with global structure (street integration). It made it possible to quantify these spatial interactions. This test assesses the structural coherence of Batna's road network and the capacity of the urban fabric to produce spaces that are legible, accessible, and conducive to social and functional use. The Pearson correlation coefficient (r), measuring the strength and direction of the linear relationship between these two variables, is equivalent to 0.375, which means that there is a moderate positive correlation between the two indicators, the more a street segment is well connected locally, the more it tends to be accessible globally, however this relationship is not strong (it is moderate), which suggests that there are other factors that influence global integration. The obtained p-value (Sig. = 0.000) indicates a highly significant

Table 2: Spearman's rho correlation analysis between connectivity and global integration in Batna city

		Connectivity		Integration [HH] R2
Spearman's rho	Connectivity	Correlation Coefficient	1.000	0.993**
		Sig. (2-tailed)	.	0.000
		N	25753	25753
	Integration [HH] R2	Correlation Coefficient	0.993**	1.000
		Sig. (2-tailed)	0.000	.
		N	25753	25753

** . Correlation is significant at the 0.01 level (2-tailed).

Table 3: ANOVA table of linear regression between connectivity and integration R2

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	33949.335	1	33949.335	4221.261	0.000 ^b
	Residual	207101.442	25751	8.042		
	Total	241050.777	25752			

a. Dependent Variable: Integration [HH] R2

b. Predictors : (Constant), Connectivity

correlation between the two variables. Being less than 0.05, it allows us to reject the null hypothesis and confirms that there is a real relationship, with less than 0.1% probability that it is due to chance. The analyzed sample includes 25753 street segments, which is a very large size. Such a large size guarantees the robustness and reliability of the results obtained, thus strengthening the statistical validity and ensuring better representativeness of the spatial phenomena studied.

The Spearman correlation coefficient (ρ) obtained is 0.993 (Table 2), indicating a strong and positive relationship between connectivity and integration R2 in the spatial network of Batna city. It also means that the two variables increase together. Concretely, the more a street segment is well connected locally, the more it tends to be well integrated into the entire road network. This strong correlation reveals a great coherence between the local and global logics of the spatial system in Batna. The two-tailed significance value (Sig. 2-tailed) obtained is 0.000, which corresponds to a p-value less than 0.001. This outcome confirms with high statistical confidence that the observed relationship reflects a genuine structural pattern rather than a random occurrence. This statistical robustness is further reinforced by the considerable size of the sample analyzed ($N = 25753$ street segments), which gives the test strong analytical power, ensures increased reliability of the results, and confers solid empirical legitimacy to the interpretation of the spatial dynamics observed in the city of Batna.

Predictive dynamics in UC: Linear regression test between Connectivity and Integration

This linear regression seeks to evaluate how spatial connectivity influences the level of integration R2 as measured by Depthmap.

The regression test produced a High F statistic ($F=4221.261$), calculated from data from UCL Depthmap software for Batna city, indicating a high level of variability explained by the model (Table 3). The associated Significance value (p-value=0.000), less than 0.001, indicates an extremely strong statistical significance. Therefore, these findings validate that the model demonstrates a robust linear correlation between the two variables. The explanatory variable (Connectivity) contributes substantially to the variation in the dependent variable, Integration R2. The ANOVA table from the regression test reveals that the sum of squares attributed to the regression is (33949.335), out of a total (241050.777). This allows us to calculate $R^2 = 0.140$. The Coefficient of determination R^2 is relatively modest, and it indicates that 14% of the variance in Integration R2 is explained by Connectivity. This result is logical within the context of spatial analysis, where other factors typically influence the Integration and mobility within the streets. Furthermore, the model is based on a very large sample size (25753), which increases the reliability of the results. The coefficient table (Table 4) provides more insights into the nature of the link between the two variables. The Unstandardized Coefficient ($B = 1.543$) indicates that a one unit increase in connectivity leads to an increase of 1.543

Table 4: Coefficients table from linear regression test between connectivity and integration

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-1.161	0.057	-20.200	0.000	-1.274	-1.049
	Connectivity	1.543	0.024	64.971	0.000	1.497	1.590

a. Dependent Variable: Integration [HH] R2

units in Integration R2. This effect is statistically robust, as evidenced by the low standard error (0.024), a high t-value (64.971), and a very high significance level (p-value= 0.000). Moreover, the standardized beta coefficient of (0.375) reflects a moderate but significant effect, confirming that connectivity significantly influences the spatial integration of the urban fabric. The 95% confidence interval for B [1.497 – 1.590], excluding the zero value, reinforces the precision and reliability of this estimate (Table 4). This result reinforces the idea that well-connected street segments are more likely to function as movement attractors within Batna's urban fabric. Moreover, these findings support the hypothesis that districts, including informal zones or those located in peripheral areas, that have successfully organized internal mobility tend to attract visitors and to meet urban users' expectations about the safety of those streets. Consequently, these urban entities are often perceived as high-quality urban spaces, where spatial configuration plays an important role in enhancing mobility, usability, and social performance. This also confirms the hypothesis that Batna city's center is the most attractive place within the urban fabric. The correlation also suggests that configuration potentially influences how urban users navigate and experience Batna city. Therefore, the relationship between spatial form and perception is measurable.

Entropy: "degree of spatial disorder and complexity of route choices"

This parameter simulated distributions according to visual constraints. Visual blockage plays a role in urban dynamics, which can encourage exploration of urban space or cause feelings of confusion and discomfort; excessive segmentation of the field of vision impairs the ability of city users to choose the trajectories. It measures the disorder and randomness applied to the way a city is developed and structured. The law of entropy states that the

costs of human activity are irrevocable and non-negotiable. The entropic aspects in the extraction, processing, and use of raw materials required for industrial production cannot be eliminated; this law suggests that natural processes generally progress toward a condition of increased disorder (Barbier, 2021).

The colors present on the entropy map are governed by the same law used in SSA, meaning that red often represents the highest values, medium to high values are represented in yellow or orange, while blue represents low values. The axial map, generated using UCL Depthmap 10 software, calculating the entropy parameter R2 Fig.15, highlights the spatial complexity of the city of Batna and the urban extension of Hamla. The level of disorder is high; this is revealed by the predominance of the color red at about 90% on the map, indicating a very complex urban network, composed of many connections and variations in the layout of the streets. Therefore, the entropy is high. The neighborhoods have developed organically and randomly, with streets added or modified over time without following an orderly pattern. The graph shown in Fig.16 shows the relationship between entropy (X-axis) and total line length (Y-axis), and the linear correlation coefficient (represented by a regression line) shows the decreasing relationship between these two variables. The points on the left side of the graph are relatively scattered, indicating low entropy values, specifically ranging from 0.31 to approximately 0.4. In this area, the line lengths vary little. On the right, points with higher entropy values (up to about 1.05) are denser and more spread out, but the line lengths also vary considerably. This indicates that systems with higher entropy have greater diversity and spatial complexity. In this logic, Zachary and Dobson (2021) used entropy to explore how urban space in Sheffield (UK) grows and functions. Also, the study of (Tang et al., 2024)

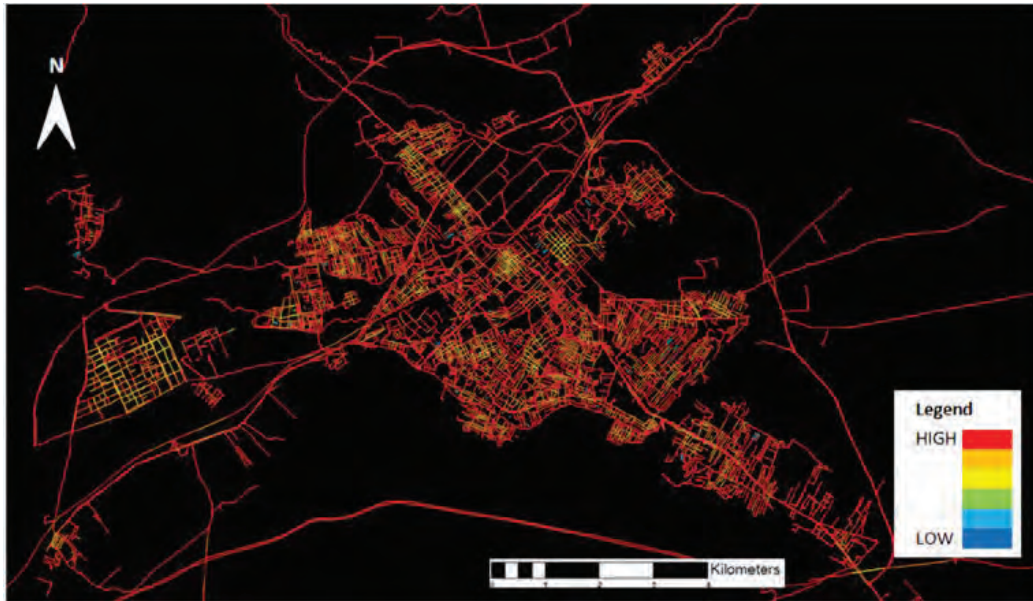


Fig. 15: Axial map_ Entropy R2 (Generated using UCL Depthmap 10- Output). Source: The authors

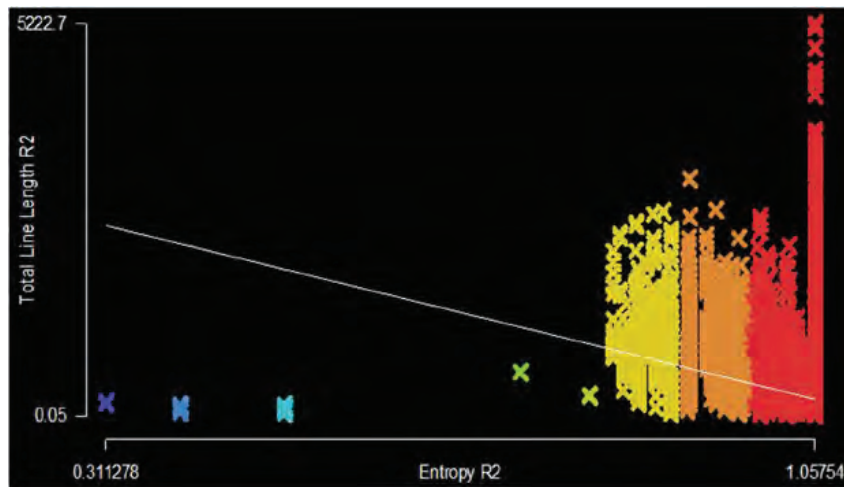


Fig. 16: A graph representing the relationship between entropy (X axis) and total line length (Y axis). Source: The authors

illustrated a localized use of entropy, where spaces with high entropic value, identified using space syntax, corresponded to the main centers of activity, thus reinforcing the interest of this measure for the intelligent management of flows in public spaces. The complexity recorded in Fig.15 may stem from dense connectivity of short segments of streets, mixed-use functions as highlighted by previous studies. Although the presence of structured districts, high

values suggested intense activity and user flows across the whole city. This urban complexity goes beyond geometric characteristics. In this context, the road network of Batna city presents corridors of movement and social interaction nodes, influencing permanently the visual perception of users and may increase or reduce the attractiveness of the city. Accordingly, QUS depends on the results of this parameter.

Table 5: Correlation analysis between Connectivity and Entropy in Batna City

		Entropy R2	Connectivity
Pearson Correlation	Entropy R2	1.000	0.288
	Connectivity	0.288	1.000
Sig. (1-tailed)	Entropy R2	.	0.000
	Connectivity	0.000	.
N	Entropy R2	25753	25753
	Connectivity	25753	25753

Table 6: ANOVA table of linear regression between Connectivity and Entropy R2

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	447.138	1	447.138	2327.894	0.000 ^b
	Residual	4946.206	25751	0.192		
	Total	5393.344	25752			

a. Dependent Variable: Entropy R2

b. Predictors: (Constant), Connectivity

Predictive dynamics in UC: Linear regression test between Connectivity and entropy

To assess the existence of a statistical link between street connectivity and spatial complexity, a linear regression test was performed on data from the UCL Depthmap software. Pearson correlation analysis reveals a low to moderate positive and significant relation between Connectivity and Entropy ($r = 0.288$, $p\text{-value} = 0.000 < 0.001$) Table 5, suggesting that the more connected a space is, the more entropy tends to increase, resulting a visual complexity and a potentially more fragmented field of vision Fig.15, but the connection is not very strong $0.1 < r < 0.3$. The linear regression performed took connectivity as the independent variable and entropy as the dependent variable. The obtained model is statistically significant ($F = 2327.894$; $p\text{-value} = 0.000 < 0.001$), from ANOVA Table 6. The Mean Square of the Error (MSE) = 0.192, compared to the total variance of entropy 5393.344, meaning that the model only explains about 8.3% of the variance, explaining only a limited proportion of the variations. The MSE, therefore, confirms that connectivity alone is not sufficient to account for the entropic complexity of urban forms. Thus, Entropy is affected by other factors, such as economic and population factors (Papadimitriou, 2022). High connectivity is aimed at improving accessibility, flow of movement, and mobility. However, the positive correlation with entropy shows that a highly connected space can also be more visually complex, and therefore less readable for the users. This attribute is not a guarantee of QUS. In a context of a

fast UG, these effects are accentuated, underscoring the need for a balance between spatial intelligibility and accessibility to maintain sustainable QUS.

Recommendations

Finally, as only three space syntax parameters were analyzed, it is recommended that future research should study other metrics, such as choice, control, and controllability, to enrich spatial analysis. Particular attention should be given to vernacular and local urban planning, refocusing on pedestrian movement, the connectivity of public spaces, and the enhancement of city entrances, which reflect the UR of the lived urban atmosphere often created by the inhabitants. These dynamics foster a strong sense of local identity and contribute to the city's vitality. Prioritizing Human experience in urban planning is a fundamental strategy to strengthen the QUS, improving spatial interactions, and increasing urban attractiveness in a context of competition between Algerian cities. Results of this study allowed proposing a structured approach to rethink the PUS, based on MQI from SSA and SST. This process brings with it an in-depth local spatial diagnosis, aiming to identify levels of connectivity, integration, and spatial complexity. It proceeds by focusing on districts with weak spatial performance, including marginalized or unplanned neighborhoods subject to social fragmentation. Areas with strong integration should be designated as strategic hubs that can drive UG. In addition, access streets to major urban attractors must be improved. The reconfiguration of

RN then becomes a priority, involving establishing open, readable, and accessible spaces in central and intermediate areas. Finally, the integration of spatial indicators from SST into urban planning studies and policies is important to frame coherently the UG, to improve the QUS, and guarantee sustainable PUS.

CONCLUSION

By mobilizing spatial configuration indicators such as Connectivity, Integration, and Entropy from axial line analysis of SSA. This analysis aimed to clarify how the configuration of the street system influences circulation patterns, social dynamics, and the trajectories of the evolution of the city. The UC analysis of Batna city revealed the direct impact of UC on QUS, PUS, and users' perception, validating the idea that the urban experience is shaped by the topological organization of space. By using data from UCL Depthmap and processing it via linear regression in SPSS, it was demonstrated that the "connectivity" variable exerts a significant effect on the level of integration ($F=4221.261$, $R^2 = 0.140$), and it also exerts a significant effect on urban complexity or entropy. These results confirmed the hypothesis that visual perception and urban interaction can be measured and explained objectively by UC. However, predictability rates 14% and 8.3% derived from linear regression tests indicated that other factors contribute to enhancing users' perception, PUS, and the QUS. The study highlighted that the best-integrated residential neighborhoods, whether located in central or peripheral areas, [Figs. 11 and 12](#), display greater fluidity for both pedestrian and car traffic, despite the complexity of both the urban structure and the route's choice. In this perspective, these parameters can be used to anticipate potential changes in urban morphology by identifying areas where low connectivity and high entropy, [Figs. 9 and 15](#) could hinder the development of quality urbanity. On the local scale, this study agrees on the fact that the city's RN constitutes an essential element for achieving spatial quality. A good layout of public spaces thus modifies the behavior of the people who frequent them and encourages greater participation in activities. The main contribution of this study lies in the comprehensive and integrated approach: neighborhoods were not analyzed in isolation, but each spatial entity was interpreted as an interconnected fragment of a larger urban whole.

This approach enabled a holistic reading of urban processes, transcending administrative boundaries and the oppositions between Batna's center and periphery. Batna must be transformed from a locality that people pass through for basic needs into a multitude of interactive spaces, where various activities can flourish in each area.

AUTHOR CONTRIBUTIONS

The first author conceived the presented study, performed the literature review and developed it, performed the analysis, interpreted the data, and prepared the manuscript text. The second and third authors verified the analytical methods, helped in the literature review, and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

ANOVA	Analysis Of Variance
B	Unstandardized Coefficient; from the Coefficients Table from the linear regression test
Beta (Standardized Coefficient)	Coefficient from the coefficients Table from the linear regression test indicates the strength and direction of the relationship between variables
F (F statistic)	Fisher's statistic is used in ANOVA
ISO	International Organization for Standardization
MQI	Measurable and Quantifiable Indicators
MSE	The Mean Squared Error
ρ	Spearman's rank correlation coefficient
PDAU (in French)	Plan Directeur d'Aménagement et d'Urbanisme (Master Plan for Development and Urban Planning)
POS (in French)	Plan d'Occupation des Sols (Land Use Plan)
PUS	Production of Urban Spaces
QUS	Quality of the Urban Space
r	Pearson Correlation coefficient
R (n, 2, 3, 5, 7)	local and global topological radius

R^2	Coefficient of determination (proportion of explained variance)
RN	The Road Network
Sig. (2-tailed)	Significance level (p-value) for a two-tailed statistical test
SPSS	Statistical Package of the Social Sciences
SSA	Space Syntax Analysis
SST	Space Syntax Theory
Std. error	Standard error, from the Coefficients Table from the linear regression test
t	from the Coefficients Table from the linear regression test; the test statistic is calculated as B divided by Std. error
UC	Urban Configuration
UCL	University College London
UG	Urban Growth
UR	Urban Reality
X axis	Horizontal axis
Y axis	Vertical axis

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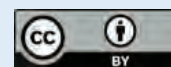
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ORIGINAL RESEARCH PAPER

Unraveling the nexus of economic growth, clean energy, and carbon emissions: An environmental Kuznets Curve-based econometric analysis

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study explored the complex relationships among economic growth, environmental policies, renewable energy adoption, and carbon emissions in various economic environments, specifically focusing on Brazil, Russia, India, China, and South Africa. These factors are investigated through the lens of the Environmental Kuznets Curve framework to discover if these emerging economies adhere to, vary from, or demonstrate distinctive variants. This study has established a framework for analyzing how development phases impact environmental degradation and evaluates the sustainability initiatives, particularly focusing on renewable energy adoption and policy change, to help lessen carbon emissions in different economic contexts.

METHODS: The study employed a range of statistical and econometric techniques to examine the relationship among economic growth, environmental policies, renewable energy adoption, and carbon emissions in Brazil, Russia, India, China, and South Africa from 1990 to 2022. This study used statistical analysis through descriptive statistics and correlation analysis. Furthermore, stationarity of the data is tested by using the Augmented Dickey-Fuller and Phillips-Perron tests. Moreover, the bounds testing is utilized to examine the cointegration among the estimated variables, whereas the Autoregressive Distributed Lag method is applied to investigate both short and long-run elasticities. By utilizing these methods collectively, a detailed investigation of whether panels of these economies align with, deviate from, or exhibit variations in the Environmental Kuznets Curve framework.

FINDINGS: The findings revealed that an inverted U-shaped trajectory between economic development and environmental pollution is evident in Russia, South Africa, Brazil, and China, suggesting that as economic development increases in these countries, environmental degradation worsens because of escalating carbon emissions. Four key points of particular interest from energy, environmental, and economic perspectives are: (1) realigning panel of these countries' industrialization and economic development policies with environment management initiatives, acknowledging that (2) an all-size-fits-all renewable energy consumption policy may not be equally effective in abating carbon emissions across all economies, (3) the incomplete coverage of consumptions sources and a subset of industries limiting a higher carbon tax's effective reduction in carbon emissions (4) financial regulations and incentives related to carbon taxes, green financing, or sustainable investments and emission reductions providing an impactful and novel avenue for enhancing financial development's carbon emissions inhibiting role.

CONCLUSION: These findings may offer policy-makers or organizations key information for sustainable development policies, which help address the conflict between economic growth and environmental quality, and may be applicable in all selected countries as well as other developing countries.

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INTRODUCTION

Certainly, climate change mitigation strategies involving the reduction of Carbon Dioxide (CO₂) emissions have brought economies at loggerheads and heightened policy inconsistency and incompatibility issues around the world. Due to the potential hazards of climate change, numerous studies have been conducted to classify the factors that might help reduce carbon emissions. Similarly, in practical terms, numerous key developments have been advanced to reduce surging CO₂ emissions levels and address climate change. To highlight a few, energy expansion (like hydroelectric power, wind, and solar), technological innovations (e.g., electric vehicles, carbon capture and storage, and energy-efficient machinery), the industrial and transportation sectors, and global collaboration. Despite their enactment, reducing CO₂ emissions still seems like a far-reaching initiative, especially across Brazil, Russia, India, China, and South Africa (BRICS) economies, where rapid growth and industrialisation policies are not matched with environmental preservation initiatives (Samour *et al.*, 2023). This grouping offers an intriguing context due to its rapid economic growth, diverse policy approaches, and substantial contributions to global emissions (Iqbal *et al.*, 2023). Examining these nations provides valuable insights into the dynamics of sustainability initiatives in economies at different stages of development, reflecting diverse policy landscapes and varied levels of environmental consciousness. In an attempt to better design effective environmental preservation strategies, several policy options have been advanced. Especially, from environmental, economic, and energy perspectives, there are four particular propositions of interest as follows. Firstly, realigning BRICS' industrialization and economic development policies with environmental management initiatives proves to be a far-reaching endeavour. Amongst the contributing factors is the unending quest to satisfy inquiries about how the Environmental Kuznets Curve (EKC) hypothesis's dynamics shape the BRICS' policies and intricate relationships with economic and environmental policies. The EKC hypothesis assumes that there is a pollution level and per capita income tends to follow an inverted U-pattern, where pollution initially rises with income and then declines after a certain threshold (López-Menéndez *et al.*, 2014). With various EKC hypothesis shapes like the

inverted U shape (Culas, 2007), U shape (Dinda *et al.*, 2000), inverted N shape (Harbaugh *et al.*, 2002), monotonically increasing (Permann and Stern, 2003) and monotonically decreasing (Egli, 2004) being in existence, it remains an interesting inquiry as to whether BRICS economies comply with, deviate from, or display variations in the EKC hypothesis. To add traction to this matter, the EKC may not appear in developing countries, despite the general belief that it occurs in developed countries. Secondly, a further investigation is required to determine whether a blanket policy (a one-size-fits-all) of renewable energy consumption policy across BRICS economies is effective in abating CO₂ emissions in light of factors specific to each country, like economic structures, policy implementation, and energy infrastructure. As it stands, attempts to explore these notions within the context of BRICS economies are a new phenomenon that has been continuously sidelined in long-standing academic debates (Ayhan *et al.*, 2023; Charfeddine and Kahia, 2019; Steckel *et al.*, 2021). Historical environmental policy trajectories have substantially affected the carbon emissions patterns of BRICS countries. To make this distinction, we identified early reforms (China) and renewable energy incentives (Brazil) as examples of early engagement and contrast them with Russia, India, and South Africa, which show late impacts or uneven enforcement. Differences in policy histories may have direct relations to the order and timing of each country's EKC and indicate the value of policy variables in the empirical model. Thirdly, though Li *et al.*, (2022) acknowledged carbon pricing policy's role in alleviating CO₂ emissions concerns, notions regarding a carbon pricing policy's potency to yield the highly coveted CO₂ emissions reduction outcomes continue to be the subject of long-standing CO₂ emissions debates. Unlike previous related studies (Li *et al.*, 2022; Steckel *et al.*, 2021), this study adds to the existing literature by further determining factors that significantly influence carbon pricing policies' ability to yield such outcomes. Contemporary attempts aimed at assessing such effects in BRICS economies are gathering momentum and are in their infancy. Lastly, although the United Nations Framework Convention on Climate Change (UNFCCC) strongly advocates for climate finance in mitigating such challenges (UNFCCC Standing Committee on Finance, 2023), the financial ability to familiarize themselves with climate change and

pursue sustainable development remains a key issue BRICS economies have to endure. With [Charfeddine and Kahia \(2019\)](#) indicating that the UNFCCC and the Kyoto Protocol remain insufficient to respond to climate change difficulties, turning to alternative avenues like financial development remains highly attractive. Despite financial development's role in such matters having been significantly emphasized and well documented academically ([Charfeddine and Kahia, 2019](#); [Lahiani, 2020](#); [Khan and Ozturk, 2021](#)), it possesses an intricate relationship with CO₂ emissions, consumption of renewable energy, and carbon pricing policy that demands further examination. In light of the above, while the existing body of literature around the EKC is increasingly overwhelming, there has been comparatively limited attention given to how renewable energy uptake, carbon pricing regimes, and financial development simultaneously impact carbon emissions across BRICS nations' varied economic contexts. This research aims to fill this void by combining these three areas into one EKC-based econometric model, representing a novel multi-country approach to the literature while taking into account both short- and long-run dynamics (using ARDL). The novel contribution of this study is to focus on country-specific heterogeneity, the effectiveness of policy, and a financial mechanism to inform environmental outcomes. Therefore, the study aims to find out how BRICS countries' industrialisation rate influences CO₂ emissions within the EKC model, assess whether a common renewable energy policy will be as effective in all BRICS countries, and finally examine the potential of financial development and whether it can help reduce emissions. Thus, these aims should position the study to provide both theory and policy-relevant contributions pertinent to sustainable development in newly industrializing countries.

Literature review

Renewable energy consumption's impact on the environment (CO₂ emissions)

It is no longer sufficient simply to impose environmental regulations and strict environmental policies to combat environmental degradation. Therefore, renewable energy is increasingly becoming one of the most effective ways to improve environmental and economic sustainability. In addition, according to [Charfeddine and Kahia \(2019\)](#),

renewable energy is one of the environmental policy issues encompassed in the environmental policy strict index, which is a composite relative policy stringency measure. According to [Gielen et al., \(2019\)](#), Renewable energy can contribute to supplying two-thirds of total global energy demand and create potentially significant reductions in the greenhouse gas emissions required to keep average global surface temperature increases below 2°C from now until 2050. Renewable energy's CO₂ emissions mitigating effects were confirmed in Turkey ([Acaroğlu and Güllü, 2022](#)), Vietnam ([Le, 2022](#)), Chile ([Kirikkaleli et al., 2022](#)), and Malaysia ([Raihan and Tuspekova, 2022](#)). On a panel level, [López-Menéndez et al., \(2014\)](#) Ordinary Least Squares (OLS) fixed effects and random effects findings on 27 European Union (EU) countries, [Al-Mulali and Ozturk's \(2016\)](#) Fully Modified Ordinary Least Squares (FMOLS) and Vector Error Correction Model's (VECM) results on 27 advanced economies, and [Charfeddine and Kahia's \(2019\)](#) Panel Vector Autoregression (PVAR) findings on 24 Middle East and North Africa (MENA) region countries confirmed that clean energy reduces CO₂ emission. The same was validated by [Wolde-Rufael and Weldemeskel's \(2020\)](#) Pool Mean Group-Autoregressive Distributed Lag (PMG-ARDL) model results within the context of BRIICTS (Brazil, Russia, India, Indonesia, China, Turkey, and South Africa). Nonetheless, [Cai et al., \(2023\)](#) found using quantile regression for BRICS countries from 1990-2020 that resource rents lead to increased CO₂ emissions, whereas [Pata \(2018\)](#) could not support, mitigating effects of REC on CO₂ emissions. [Danish et al., \(2019\)](#) found a positive and insignificant relationship between REC and CO₂ emissions in South Africa but a negative and significant relationship with CO₂ emissions in Brazil, China, Russia, and India. Of all empirical work, there appears to be no agreement among researchers about the relationship between REC and CO₂ emissions because single-country and panel data analysis studies are generally mixed overall. This study is limited to presenting and discussing only single-country results in the context of the economies of BRICS, as mentioned in the previous paragraph.

Carbon pricing policy's impact on the environment (CO₂ emissions)

[Green \(2021\)](#) presents carbon pricing as an efficient, flexible, and low-cost pathway to GHG reductions.

Because of this belief in the efficacy of carbon pricing, it is widespread and growing. Already, 22% of global emissions are subject to carbon pricing through 30 carbon taxes and 31 emissions trading schemes (World Bank, 2020). A carbon tax adds a charge on fuel or energy use; if someone emits more than their allowance, they can purchase more; if they emit less, they can sell their allowances or bank them. While it is an important policy tool for lowering CO₂ emissions, the literature on carbon pricing policy is still in its infancy. Apart from being limited to specific nations, carbon pricing policies in mitigating CO₂ emissions are another area subject to debate. For instance, Haites (2018) discovered that carbon taxes in European countries resulted in small reductions of 'up to 6.5% over several years' and that countries without a carbon tax reduced emissions faster than those with a carbon tax. On the other hand, Green (2021) established that the aggregate reductions from carbon pricing on emissions are generally limited between 0% and 2% per year. Li et al., (2022) economic dispatch model results on five provinces comprising China's Southern Power Grid unearthed that carbon pricing raises overall power system costs considerably, irrespective of low carbon prices. Another meta-review investigates several studies of the British Columbia carbon tax, indicating that drops between 2008 and 2014 vary between 5% and 15% below a counterfactual reference level (Green, 2021). They do, however, point out that no studies have been conducted to investigate leakage to neighbouring jurisdictions. Aside from responding to these empirical voids, the current study weighs and validates such examinations on a yet-to-be-modelled platform involving BRICS economies. Overall, a carbon pricing policy's effectiveness in mitigating CO₂ emissions remains vital for creating a Sustainable Development Mechanism and achieving the 2015 Paris Agreement goals on climate change. Amid such observations, it, therefore, remains an interesting inquiry as to whether carbon pricing policies yield the highly coveted CO₂ emissions reduction outcomes across BRICS economies with distinct economic, social, and structural characteristics. Unlike previous studies, this study extends further to determine how this aligns or hampers their rapid industrialisation and growth initiatives.

Financial development's impact on the environment (CO₂ emissions)

Undoubtedly, financial development is an

instrumental factor in economic growth today since it facilitates capital accumulation through the accumulation and management of reserves, enhances essential knowledge about investment operations, and allocates money wisely. In light of the EKC hypothesis' inverted U-shape that suggests higher levels of economic growth increase CO₂ emissions (López-Menéndez et al., 2014), the indirect effects of financial development on greenhouse gas emissions are evident in this case, especially when manufacturing activities are increased (Aye and Edoja, 2017). According to Charfeddine and Kahia (2019), in terms of environmental quality, the financial sector can have a catalytic function in the reduction of emissions through innovations in technology in the energy supply sector. Furthermore, financial development has the potential to boost the fight against environmental deterioration through CO₂ reduction. It can do this by being a funding channel for projects by stock markets and banks, and providing financial resources for productive activities (Charfeddine and Kahia, 2019). In this view, environmental degradation declines as financial progress is made. Additionally, by transforming the energy sector into a more efficient one, a well-developed financial sector can promote investment activities, reduce borrowing costs, and restrain the spread of energy emissions (Charfeddine, 2017; Tamazian et al., 2009). Financial development helps not only to attract foreign direct investment, support research and development initiatives, and increase the level of economic activity, but also has an impact on the quality of the environment through green-related investments (Charfeddine and Al-Malk 2018; Hayat et al., 2018). Expanding on this idea further, Awosusi et al., (2022) applied a quantile regression approach to data from Uruguay (1990-2018), and Usman et al., (2022) utilized an ARDL study with Pakistan data from 1990-2017, to find that financial development and renewable energy hurt CO₂ emissions. Khan and Ozturk (2021) applied several different Generalized Method of Moments (GMM) and system GMM techniques to a sample of 88 developing countries (2000-2014) and confirmed that the Lawrence curve is inequitably shaped concerning the EKC, while also substantiating the pollution-abating nature of financial development. Nevertheless, financial development can yield negative effects on the environment caused by manufacturing activities

that lead to pollution levels to increase (Charfeddine and Kahia, 2019). In their panel data model using a partially linear functional-coefficient, Xu *et al.*, (2021) found further evidence that the effect of financial development on CO₂ emissions transitioned from negative to positive as energy consumption and industrialization also increased. Although there was evidence of an inverted U-shape EKC in both Khan and Ozturk (2021) and Xu *et al.*, (2021). Xu *et al.*, (2021) revealed that an increase in financial development was associated with increasing CO₂ emissions only when per-capita income was less than \$1100 or greater than \$8100. While there is a consensus in the literature regarding the theoretical effects of renewable energy consumption, carbon pricing policy, and financial development on environmental quality, previous empirical work has found it difficult to concur on the same conclusion. Validating the EKC hypothesis across countries like BRICS has been a far-reaching objective for several time series data studies. To contribute to this literature, this study used 5 ARDL econometric models for BRICS economies. The adopted ARDL model form is discussed in detail in the next section.

MATERIAL AND METHODS

The model

The current study was theoretically underpinned by the EKC hypothesis to determine whether BRICS economies' environmental impacts follow similar or divergent patterns. A further contribution of the EKC hypothesis is that it will enable us to identify Income Turning Points (ITPs) where increasing income results in a decrease in CO₂ emissions, which may be a reflection of environmental awareness, technology adoption, or policy changes. As suggested by Grossman and Kruger (1995), an important component of this model is that pollution increases at the beginning of economic progress, whereas the trend reverses following a certain income level (ITP). This means that at levels of high-income levels, economic progress results in an enhancement in environmental quality. With contrasting outcomes like the inverted U shaped (Culas, 2007), the U shaped (Dinda *et al.*, 2000) and inverted N shaped (Harbaugh *et al.*, 2002), and scant empirical examinations within the context of BRICS economies characterising such propositions, this study theoretically commence by acknowledging BRICS rapid industrialisation and

economic growth's adverse impact on environmental quality as suggested by Grossman and Kruger (1995). According to López-Menéndez *et al.*, (2014), the Kuznets Curve is a polynomial type of function as follows in Eq. 1 and Eq. 2:

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \mu \quad (1)$$

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \beta_3 X^3 + \mu \quad (2)$$

In this scenario, X signifies the economic development levels, usually assessed using Growth Domestic Product (GDP) per head of population. In addition to water pollution, fine smoke, municipal waste, deforestation, and air pollution, Y is also an indicator of environmental degradation. However, emphasis is usually placed on CO₂ emissions. Despite the EKC hypothesis serving as an instrumental framework for assessing economic growth's impact on the environment, its theoretical propositions always spark debates in various fields. In the environmental management and energy policy context, the EKC hypothesis is not confined to following environmental regulations and foreign direct investments (Orubu and Omotor, 2011) nor foreign trade (Lee and Roland-Holst, 1997) as suggested. With numerous variables at play in this context, a nuanced understanding of environmental quality management is provided by acknowledging Renewable Energy Consumption's (REC) role in such matters in abating pollution (Charfeddine and Kahia, 2019). Furthermore, by integrating financial development's increasingly important role and the significance of sustainability initiatives involving carbon pricing policies into such examinations, a realistic picture of BRICS' environmental management and energy policy is projected based on the EKC framework. Due to the possibility of obtaining several quadratic functions and cubic form EKC hypotheses, as well as the lack of consistency in terms of the association between environmental quality and economic growth, these propositions have significant implications for the BRICS economies' rapid industrialization and economic growth policies. This study applied a multi-country ARDL approach to analyse the dynamics of short and long-term effects. The simultaneous examination of multiple BRICS nations using an ARDL approach provides valuable insights into common

trends and variances in the intricate relationships between CO₂ emissions and key variables for policymakers. Unlike studies limiting focus to the environment-output-energy relationship under the basic EKC context (Aroui *et al.*, 2012; Yavuz, 2014), this study recognises policy decisions and the financial sector's role in such matters. Ultimately, this study provided a comparative approach by integrating the EKC hypothesis propositions with Renewable Energy Consumption (REC), Carbon Pricing Policy (CPP), and Financial Development (FD) across BRICS economies. This was instrumental in providing a nuanced understanding of the diverse policy landscapes within the group. Thus, to formulate the multi-country ARDL model, Carbon Emissions (CE) were regressed on Y, quadratic income (Y²), REC, CPP, and FD. The adapted form of this model employed in this paper is as follows in Eq. 3:

$$CE = (Y, Y^2, REC, CPP, FD) \quad (3)$$

According to Bilgili *et al.*, (2016), log-linear models produce more efficient results than linear models. As a result, Eq. 4 is developed following improvements made to related models by Orubu and Omotor (2011) and Saboori *et al.*, (2012) as follows:

$$\begin{aligned} \ln CE = & \alpha + \beta_1 \ln Y + \beta_2 \ln Y^2 + \\ & \beta_3 \ln REC + \beta_4 \ln CPP + \beta_5 \ln FD + \varepsilon_{it} \end{aligned} \quad (5)$$

Where α = constant, β_1 to β_5 are parameters and ε_{it} is the error term. Assuming that the inverted U-shaped EKC relationship between CO₂ and income (Y) holds, $\beta_1 < 0$ and $\beta_2 > 0$. β_3 and β_4 are expected to adversely impact CO₂ emissions. While financial development may lack the propensity to directly impact CO₂ emissions, it is expected to contribute towards abating CO₂ emissions and its coefficient (β_5) can be greater or smaller than zero. Apart from dealing with outliers, the variables were converted to logarithms to determine the CO₂ emissions' elasticity responses to changes in Y, REC, CPP, and FD. Keeping these caveats in mind, this study shall apply 5 ARDL (Auto-Regressive Distributive Lag) models of order p for the dependent variable, and order q for the explanatory variable, as follows in Eq. 5:

$$ce_{it} = \sum_{j=1}^p \beta_{ij} ce_{i,t-j} + \sum_{j=0}^q \gamma_{ij} X_{i,t-j} + \mu_i + \varepsilon_{it}$$

Where X_{it} the vector of explanatory variables is defined in Eqs. 3 and 4 can be re-parameterized as an error-correction form as follows in Eq. 6:

$$ce_{it} = \mu_i + \varphi_i (ce_{i,t-1} - X_{it}) + \sum_{j=1}^{p-1} \lambda_{ij} ce_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij} X_{i,t-j} + \mu_i + \varepsilon_{it} \quad (6)$$

X_{it} represents the vector of independent variables defined above, where Δce_{it} is the annual growth per capita of CO₂ emissions for country i at time t . The parameters λ and δ rank the short-run coefficients on each lag of the dependent and independent variables, respectively. ψ represents the long-run coefficient, and φ_i represents the coefficient on the error-correction term, which measures the pace at which CO₂ emissions adjust to return towards their long-run equilibrium after the changes in the independent variables (X_{it}). That is, following Aksoy (2019), the criterion $\varphi_i < 0$ is important evidence of a long-run relationship. Thus, a negative and statistically significant value of φ_i suggests there is evidence of cointegration between ce_{it} emissions and its determinants. In advance of this, this study tested the variables for unit roots, using both the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) stationarity tests to avoid the possibility of spurious outcomes.

Data

This paper employs World Bank country indicator time series data for 5 BRICS economies (Brazil, Russia, India, China, and South Africa) for the period 1990-2022. The variables are carbon emissions (percentage change in CO₂ emissions), economic growth (% GDP growth), Renewable Energy Consumption (REC) (% of total final energy consumption), Carbon Pricing Policy (CPP) (greenhouse gas emissions as a percentage of GDP) and Financial Development (FD) (domestic credit to the private sector (%)). According to the economic growth and CO₂ emissions scores presented in Table 1. Renewable Energy Consumption is defined as the percentage of total final energy consumption that came from renewable sources, from World Bank indicators, and used as a proxy for both the quantity of clean energy investments and the effectiveness of renewable energy policies in BRICS economies.

Table 1: Descriptive analysis

Country	Variable	Descriptive stats.	
		MN	SD
Brazil	CE	-1.80	0.14
	EG(Y)	1.84	0.54
	REC	4.44	0.09
	CPP	1.73	0.09
	FD	3.89	0.37
Russia	CO ₂ E	2.77	0.09
	EG(Y)	2.60	0.69
	REC	1.26	0.06
	CPP	-0.16	0.65
	FD	3.42	0.51
India	CO ₂ E	-1.13	0.10
	EG(Y)	1.78	0.36
	REC	3.72	0.17
	CPP	0.74	0.18
	FD	3.60	0.33
China	CO ₂ E	1.47	0.51
	EG(Y)	2.15	0.33
	REC	2.93	0.43
	CPP	1.85	0.41
	FD	4.78	0.23
South Africa	CO ₂ E	-0.57	0.06
	EG(Y)	2.16	0.35
	REC	2.45	0.32
	CPP	2.36	0.06
	FD	4.72	0.13

MN=Mean and SD=Standard Deviation

Policy-specific instruments are not part of the model directly; however, cross-country heterogeneity in terms of the design, implementation, and enforcement of renewable energy policies was partially captured. Therefore, the analysis of added impacts of policy enables some differentiation of policies across countries, based on varying levels of development and institutional context. [Cai et al., \(2023\)](#) discoursed that about 38% of the global CO₂ emissions are accounted for by BRICS economies. Countries, comprising Brazil, Russia, India, China, and South Africa, comprise a mix of rapidly growing economies from different regions with considerable economic weight and varying developmental stages. The findings of the BRICS group show varying levels of development. For instance, unlike India and Brazil, with low mean scores of 1.78 and 1.84, respectively, Russia, South Africa, and China recorded high economic growth mean scores of 2.60, 2.16, and 2.15. An increase

in economic growth is often accompanied by an increase in transportation, industrial activities, and energy consumption, thereby resulting in an increase in CO₂ emissions in Russia, South Africa, and China, which follows the EKC hypothesis. There are, however, negative CO₂ emissions, mean scores of -1.80, -1.13, and -0.57 observed in Brazil, India, and South Africa, respectively, which signifies that these countries emit lower amounts of CO₂ than Russia and China. However, the key is to manage the growth sustainably to mitigate the effects of carbon emissions and ensure environmental protection worldwide. The scholarship's proposition to integrate environmental management initiatives with economic and financial sector activities and an energy policy gains further traction when observations of [Fig. 1](#) are considered.

Though Russia observed a decline in per capita consumption-based CO₂ emissions from 13.8t/person in 1990 to 5.2t/person in 1992, 9.4t/person,

Examine the EKC framework and environmental quality

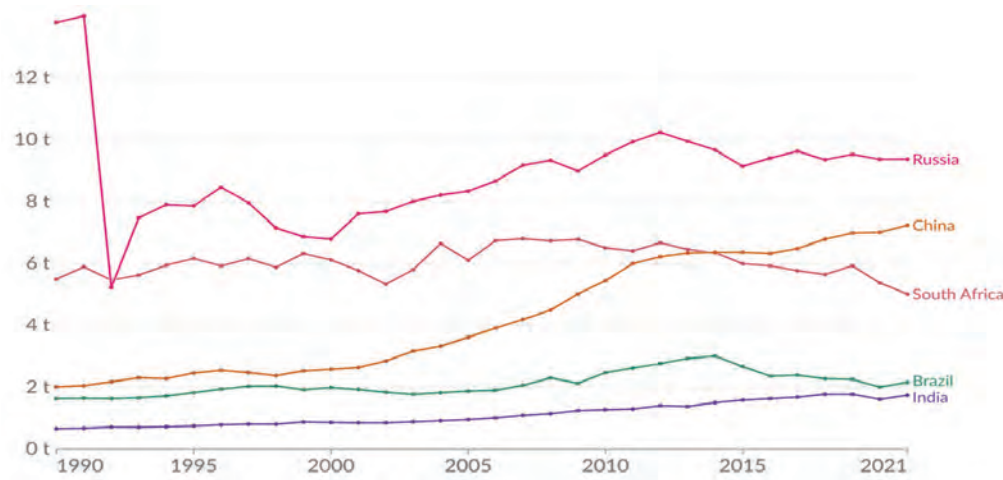


Fig. 1: Per capita consumption-based CO₂ emissions (Source: World In Data, 2023)

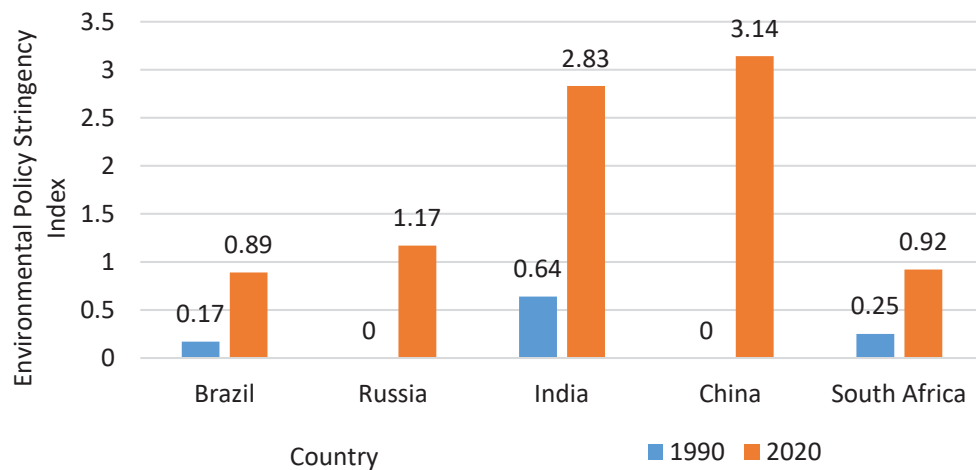


Fig. 2: Environmental Policy Stringency Index (Source: Authors)

the demand for such novel initiatives has been highly coveted as China, South Africa, Brazil, and India registered high per capita consumption-based CO₂ emissions in 2021. In light of the statistically significant changes recorded in China, South Africa, Brazil, and India, respectively, in terms of percentage changes of 263.64%, -14.1%, 46.67%, and 65%, this study expresses concern over the impact of CO₂ emissions on their environment. This study also highlights empirically sidelined yet important influences of country-specific factors on environmental management across the BRICS economies. To

support the scholarship's objectives, Fig. 2 shows that the Environmental Policy Stringency Index (EPSI) has increased among BRICS economies, indicating a more demanding regulatory environment regarding environmental protection and sustainability. This indicates that, despite existing policies, CO₂ emissions may not be reduced or mitigated effectively. Despite higher stringency indexes suggesting stricter regulations and standards, CO₂ emissions continue to increase, as illustrated in Fig. 2. EPSI are scored on a 0–6 scale increasing in stringency (0 is assigned when the instrument is not present in a country), and 6

Table 2: Unit root tests

Country	Variable	ADF		PP		Decision
		t. stat.	Prob.	t. stat.	Prob.	
Brazil	LCO ₂ e	-4.5620	0.0000	-4.617	0.0000	I(I)
	LCPP	-4.1281	0.0000	-4.4807	0.0000	I(I)
	LREC	-4.1215	0.0000	-4.4283	0.0000	I(I)
	LFD	-4.0921	0.0000	-3.7020	0.0000	I(0)
	LEG	-4.4000	0.0000	-4.6183	0.0000	I(I)
Russia	LCO ₂ e	-3.8246	0.0000	-4.1257	0.0000	I(I)
	LCPP	-4.5783	0.0000	-4.5783	0.0000	I(I)
	LREC	-4.6202	0.0000	-4.7354	0.0000	I(I)
	LFD	-4.4586	0.0000	4.8095	0.0000	I(0)
	LEG	-5.097	0.0000	-4.7764	0.0000	I(0)
India	LCO ₂ e	-3.7425	0.0000	-3.7425	0.0000	I(I)
	LCPP	-3.9344	0.0000	-3.9344	0.0000	I(I)
	LREC	-5.4817	0.0000	-4.8451	0.0000	I(I)
	LFD	-4.1897	0.0000	-4.0670	0.0000	I(0)
	LEG	-7.4205	0.0000	-7.4205	0.0000	I(0)
China	LCO ₂ e	-4.2426	0.0000	-4.2426	0.0000	I(I)
	LCPP	-4.9375	0.0000	-4.1087	0.0000	I(I)
	LREC	4.5660	0.0000	4.5660	0.0000	I(I)
	LFD	-4.359	0.0000	-3.769	0.0000	I(0)
	LEG	-7.720	0.0000	-4.3167	0.0000	I(0)
South Africa	LCO ₂ e	-4.167	0.0010	-4.724	0.0010	I(I)
	LCPP	-46.744	0.0000	-24.095	0.0000	I(I)
	LREC	-10.874	0.0000	-10.075	0.0000	I(I)
	LFD	-4.282	0.0040	-4.262	0.0040	I(0)
	LEG	-6.560	0.0000	-10.322	0.0000	I(0)

denotes the most stringent policies. Accordingly, this raises questions about the adequacy, enforcement, or effectiveness of the current policies.

In light of these observations, this study proposed that addressing rising CO₂ emissions crucially demands a shift towards renewable energy sources and implementing a carbon pricing policy by introducing economic incentives to reduce carbon emissions. Promoting financial development is pivotal in supporting the transition to a low-carbon economy to enhance effectiveness in abating CO₂ emissions. However, without adequate empirical validation, such propositions can lose huge practical grounds. Hence, following the modelling of the purported interactions, the study findings are presented in the next section.

RESULTS AND DISCUSSIONS

Unit root tests

By computing the ADF and PP unit root tests, the results of Table 2 show that all five estimated variables are integrated at I(0) and I(1) across the BRICS as projected by both tests, which proves that there were no unit roots. Apart from being an essential condition of avoiding an ARDL crash (Nkoro

and Uko, 2016), this is vital for reducing spurious relationships and ensuring that more robust and valid statistical inferences are drawn from the ARDL model.

Panel data estimations are a growing norm in contemporary related examinations. Hence, motivated by the sidelining of multi-country level ARDL analyses by related studies, this study proceeded to ascertain CO₂ emissions, carbon pricing policy, renewable energy consumption, financial development, and economic growth's short-run ARDL dynamics across BRICS economies.

Short-run ARDL estimation

In the short run, lagged variables pose distinct effects on the main variables across BRICS economies, as shown in Table 3. This indicates that historical or past factors affecting CO₂ emissions (such as economic growth, renewable energy consumption patterns, carbon pricing policy implementations, and financial development) have varying impacts on present emissions levels across BRICS nations. As a result, a one-size-fits-all policy approach for mitigating CO₂ emissions across BRICS countries might be ineffective. Policymakers should consider country-specific strategies. In that regard, policymakers should

Table 3: Short-run ARDL estimation

	Brazil	Russia	India	China	South Africa
LCP	1.855(11.128)*	0.124(2.740)	0.5146 (15.671)*	1.164(34.888)*	-2.469(-2.455)**
LCP(-1)	-3.232(-9.724)*	-0.197(-2.280)**	1.3193 (15.671)*	-1.846(-9.351)*	-2.469(0.016)**
LCP(-2)	1.374(6.643)*	0.069(1.483)	-0.3539 (15.671)*	0.748(9.330)*	-
LCO ₂ E (-1)	1.793(31.931)*	1.789(30.990)*	-0.7029 (15.671)*	1.544(21.302)*	1.627(0.000)
LCO ₂ E (-2)	-0.805(-14.093)*	-0.806(-13.673)*	0.1748 (15.671)*	-0.604(-9.351)*	-0.736(0.000)
LEG	-0.003(-1.719)	0.013(5.075)*	0.0142 (15.671)*	0.004(2.179)**	0.008(0.009)
LEG(-1)	-	-0.021(-5.463)*	-0.0123 (15.671)*	-0.010(-2.684)**	-0.008(0.027)**
LEG(-2)	-	0.010(4.429)*	0.0013 (15.671)*	0.005(2.008)**	0.003(0.500)
LEG(-3)	-	-	0.0002 (15.671)*	0.002(1.553)	0.0002(0.953)
LEG(-4)	-	-	(15.671)*	-	0.0058(0.127)
LFD	-0.0004(-0.248)	-0.25(-2.055)**	(15.671)*	0.060(5.528)*	-2.020(0.068)
LFD(-1)	-	0.048(2.171)**	(15.671)*	-0.091(-4.684)*	-
LFD(-2)	-	-0.026(-2.163)**	(15.671)*	0.037(3.433)*	-
LFD(-3)	-	-	(15.671)*	-	-
LFD(-4)	-	-	0.046 (15.671)*	-	-
LREC	0.005(0.365)	-0.237(-7.599)*	-0.029(15.671)*	-0.144(-9.741)*	-0.035(0.012)**
LREC(-1)	-	0.422(8.138)*	1.121(1.861)	0.198(6.920)*	-
LREC(-2)	-	-0.192(-6.129)*	-0.361(-0.624)	-0.059(-3.249)**	-
LREC(-3)	-	-	-0.008(-0.014)	-	-
LREC(-4)	-	-	0.738(1.176)	-	-
LREC(-5)	-	-	-0.970(-2.860)*	-	-
C	-0.035(-0.392)	0.066(2.364)*	0.107 (15.671)*	-0.055(-3.597)*	-0.004(0.922)
CointEq(-1)	-0.012(-3.066)*	-0.017(-4.448)*	-0.009 (-7.510)*	-0.060(-5.586)*	-0.111(-5.142)*
R ²	0.8011	0.9985	0.8042	0.9922	0.9907
Adj. R ²	0.7962	0.9983	0.7661	0.9915	0.9898
F-stat.	467.812	532.157	463.304	128.493	109.89
DW stat.	1.992	2.008	2.025	1.822	2.024

Values in parentheses show t-statistics while * and ** indicate statistical significance at 0.01 and 0.05 levels, respectively.

develop flexible and dynamic policy frameworks that can adapt to the changing impacts of lagged variables.

Table 3 further shows that South Africa has a higher speed of adjustment of 11.1% compared to China (6%), Russia (1.7%), Brazil (1.2%), and India (0.9%) as denoted by the ECTs. Though lower, this denotes a higher level of economic resilience. Thus, South Africa takes a longer period to recover from disturbances or shocks compared to China, Russia, Brazil, and India, respectively. In contrast to panel regression analysis, these findings direct attention to policy and structural factors demanding targeted and proactive policy interventions across BRICS economies. With predictive accuracies of 80.11%, 99.85%, 80.42%, 99.22%, and 99.07%, evidence of the relationships under investigation is convincing and credible. This carries huge weight in renewable energy policy and decision-making initiatives.

Bounds test

Table 4 shows the findings of the bound tests. In a quest to establish the long-term dynamics between CO₂ emissions, carbon pricing policies, renewable

energy consumption, financial development, and economic growth in BRICS economies, long-run cointegration was confirmed across Russia, India, China, and South Africa, but not in Brazil. Unlike Wolde-Rufael and Weldemeskel's (2020) 1993-2014 PMG-ARDL estimator results on BRIICTS, revealing cross-sectional dependencies, our findings suggest country-specific effects or heterogeneity across BRICS. This entails that a one-size-fits-all policy approach to CO₂ emissions is, to some extent, not appropriate for the entire BRICS economies. In that context, highly coveted focused interventions addressing the specific needs of individual BRICS economies can be more effective than generic CO₂ emissions policies. Therefore, it is pivotal to implement tailored CO₂ emission strategies that consider the specific environmental, social, and economic characteristics of each BRICS economy.

Long-run ARDL estimation results

This section provides the long-run multi-country ARDL results reported in Table 5. According to the long-run ARDL estimation results, mixed inferences

Table 4: Bounds test

Country	Significance	I(0) Bound	I(1) Bound	F-statistic	Long-run exist
Brazil	5%	2.56	3.49	1.503	No
Russia				3.571	Yes
India				11.568	Yes
China				4.975	Yes
South Africa				3.973	Yes

Table 5: Long-run ARDL estimation

	Brazil	Russia	India	China	SA.	Net effect
C	1.49[0.54]	3.97[(3.69)*]	3.08[5.14]*	-0.92[-5.08]*	-0.04[-0.10]	-
LY-->LCO ₂ E	-0.01[4.26]*	-0.72[6.71]*	0.42[-5.38]*	-0.18[5.52]*	-0.89[3.91]*	-1.38
LY ² -->LCO ₂ E	0.04[0.30]	0.09[1.03]	-0.39[-4.26]*	-0.04[2.69]*	0.06[2.15]**	0.159
LREC-->LCO ₂ E	-0.06[0.90]	-0.47[0.59]	0.13[3.75]*	-0.08[-2.64]*	-0.32[2.76]*	-0.512
LCPP-->LCO ₂ E	-0.35[0.15]	-0.22[-2.88]*	0.07[1.47]	1.10[29.25]*	0.79[-1.69]	1.387
LFD-->LCO ₂ E	-0.05[0.36]	-0.25[-2.93]*	0.10[-8.52]*	0.11[3.79]*	-0.19[2.05]**	-0.273

Values in parentheses show t-statistics while * and ** indicate statistical significance at 0.01 and 0.05 levels, respectively.

can be drawn from each other in terms of the projected different EKC relationship types. Unlike findings drawn from India ($\beta_{23}=-0.39^*$) and [Naradda Gamage et al., \(2017\)](#) rejecting a negative scenario for the EKC hypothesis, an inverse U-shaped path can be observed between economic development and environmental pollution in Russia, South Africa, Brazil, and China. A declining pattern of economic growth's effects on CO₂ emissions spanning from Russia ($\beta_{22}=0.09$), South Africa ($\beta_{25}=0.06^{**}$), Brazil ($\beta_{21}=0.04$) to China ($\beta_{24}=0.04^*$), confirms differences in economic and institutional dynamics' effects on the environment across BRICS economies. The EKC patterns contrast across BRICS nations, as Russia, South Africa, Brazil, and China display a classic inverted U-shaped pattern, India displays a slight bit of a heterogeneous deviation. This, to some extent, is suggestive of the differences in timing of each economy achieving the turning point of decreasing emissions with economic growth. For example, India's EKC turning point seems to occur earlier/later (usual format would have you specify it) in time, suggesting that structural economic factors and stages of industrialization can impact the environmental consequences of growth quite differently.

According to [Table 5](#), promoting renewable energy consumption highly mitigates CO₂ emissions in Russia by 47%, followed by South Africa, China, and Brazil with reduction levels of 32%, 8%, and 6%, respectively. A significant inelastic increase in CO₂

emissions of 0.13t is observed in India following an increase in renewable energy consumption, as depicted in [Table 5](#). With an observed net elastic carbon pricing policy effect of 1.387, CO₂ emission increments observed in China, South Africa, and India outweigh CO₂ emission reductions observed in Brazil and Russia for each marginal price increase of \$1/tCO₂. [Table 5](#) reports that a 1-unit improvement in financial development levels increases CO₂ emissions in India and China by 10% and 11%, respectively, but lowers CO₂ emissions in Brazil, Russia, and South Africa by 5%, 25%, and 19%, respectively.

Sensitivity analysis

Concerning the model diagnostics tests, the redundancy test was applied to ascertain whether carbon pricing policy, renewable energy consumption, financial development, and economic growth were jointly insignificant. [Table 6](#) shows that the variables were jointly significant across Brazil ($\chi^{2RT}=0.946^*$), Russia ($\chi^{2RT}=2.223^*$), India ($\chi^{2RT}=6.238^*$), China (0.366*), and South Africa (0.333*) in influencing carbon emissions. Thus, taking into consideration carbon pricing policy, renewable energy consumption, financial development, and economic growth, this study offers reliable, valid, and robust explanations of variations in BRICS economies' CO₂ emissions levels.

Stability tests

The provided [Fig. 3](#) stability tests prove that the

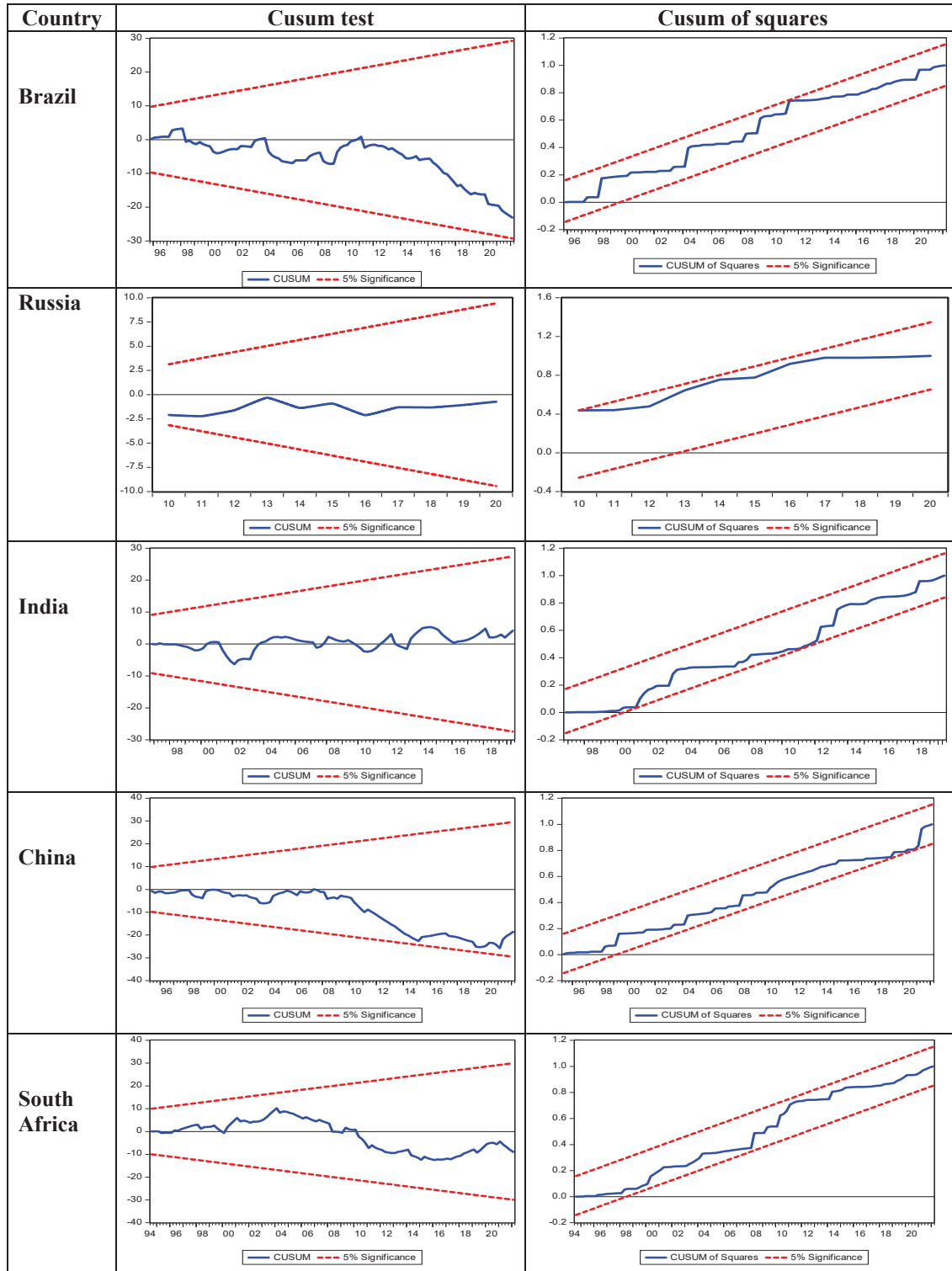


Fig. 3: Stability tests

Table 6: Sensitivity analysis

Country	χ^{RT}	χ^{2RR}	χ^{2BR}	χ^{2AR}	χ^{2SC}	χ^{2N}
Brazil	0.946 (0.325)	32.801 (0.000)	1.608 (0.413)	0.068 (0.793)	0.669 (0.485)	499.58 (0.000)
Russia	2.223 (0.139)	25.459 (0.000)	4.663 (0.120)	0.465 (0.493)	0.025 (0.971)	107.915 (0.000)
India	6.238 (0.000)	6.238 (0.000)	0.0000 (0.0000)	6.238 (0.000)	6.238 (0.000)	6.238 (0.000)
China	0.366 (0.694)	821.539 (0.000)	1.551 (0.1078)	0.006 (0.937)	6.238 (0.000)	1.791 (0.132)
South Africa	0.333 (0.740)	6.238 (0.000)	6.238 (0.000)	0.045 (0.830)	0.092 (0.9019)	48.285 (0.000)

p-values in ().

Table 7: Robustness through alternative estimation method (FMOLS)

	Brazil	Russia	India	China	SA.
C	1.73[2.14]**	2.88[4.08]*	2.67[2.23]**	-3.49[-7.02]*	-2.65[-2.24]**
LY-->LCO ₂ E	-0.02[2.43]**	-0.69[4.48]*	0.38[-3.89]*	-0.16[8.87]**	-0.78[4.65]**
LY ² -->LCO ₂ E	0.07[0.78]	0.12[1.78]***	-0.44[-5.34]*	-0.06[3.38]*	0.06[2.29]**
LREC-->LCO ₂ E	-0.09[1.83]***	-0.89[0.98]	0.17[2.31]**	-0.09[-2.58]*	-0.29[3.09]*
LCPP-->LCO ₂ E	-0.19[0.33]	-0.31[-2.33]**	0.28[1.08]	0.10[2.25]**	-0.81[-1.79]**
LFD-->LCO ₂ E	-0.10[0.45]	-0.31[-3.15]*	0.14[-6.97]*	0.09[3.91]*	-0.21[1.89]***

Values in parentheses show t-statistics while *, **, and *** indicate statistical significance at 0.01, 0.05, and 0.10 levels, respectively.

interactive connections linking CO₂ emissions with renewable energy consumption, carbon pricing policy, financial development, and economic growth are stable during the period 1990 to 2022 across BRICS economies. As a result, the estimated ARDL models provide valuable insights for decision-making, process monitoring, and model diagnostics across various fields.

Robustness Analysis

The Fully Modified Ordinary Least Squares (FMOLS) method is used for robustness testing to validate the long-run relationship discovered from the ARDL framework. FMOLS deals with serial correlation and endogeneity in cointegrated regressions, making it a valid alternative estimation technique, which increases the reliability of the findings by providing a comparison for possible biases induced by ARDL's estimation. In this study, the FMOLS is shown in Table 7, and it can be seen that nearly all the coefficients and their respective signs are in agreement with those found in the ARDL model for all countries, demonstrating the robustness and stability of the finding initially asserted. Therefore, we are confident in the long-run associations.

Post-estimation validation tests

The results from the diagnostic tests are shown in Table 8, which indicate that the ARDL models are well specified and have been bootstrapped in terms of the requirements of the ARDL assumptions for all BRICS countries. The Breusch-Godfrey LM test concluded that there is no evidence of serial correlation since the p-values were all above the 0.05 significance level. Similar results were achieved using the Breusch-Pagan-Godfrey test, which confirmed that there is no heteroskedasticity for all BRICS countries and that the residuals are homoscedastic for the fitted values. The Jarque-Bera test results indicated that the residuals are normally distributed for all BRICS countries, and the p-value was significantly above the 0.05 level of significance for all BRICS countries. Models also successfully passed the Ramsey RESET test, indicating that by and large the models were correctly specified and there were no serious misspecification issues. Finally, the Durbin-Watson statistics were all found to be close to 2, implying that there were no serious problems of autocorrelation. Overall, the econometric properties of the models appear to be satisfactory.

Table 8: Diagnostic tests outcomes

Tests	Brazil F-statistic	Russia F-statistic	India F-statistic	China F-statistic	SA. F-statistic
Breusch-Godfrey LM test for serial correlation	0.404 [0.806]	0.724 [0.937]	0.387 [0.114]	0.449 [0.564]	0.198 [0.103]
Breusch-Pagan-Godfrey test for heteroskedasticity	1.392 [0.249]	0.882 [0.243]	2.117 [0.198]	1.267 [0.165]	2.076 [0.876]
Jarque-Bera test for normality	1.503 [0.511]	2.034 [0.944]	1.164 [0.768]	1.687 [0.257]	0.985 [0.496]
Model Specification test: Ramsey RESET	2.101 [0.158]	1.734 [0.223]	2.284 [0.185]	1.850 [0.878]	0.910 [0.145]
Durbin-Watson stat.	1.992	2.008	2.025	1.822	2.024

Values in parentheses show p-values

DISCUSSION

Firstly, while an inverted U-shaped trajectory between economic development and environmental pollution is evident in Russia, South Africa, Brazil, and China, an inverted U-shaped relation exists in India. Contrary to India and [Gamage et al.,’s \(2017\)](#) findings, this suggests that as economic development increases in Russia, South Africa, Brazil, and China, environmental degradation worsens because of escalating CO₂ emissions. In contrast to the other BRICS countries, India is not clearly showing an inverted-U-shaped EKC. This is due to its unique economic structure that still transitions from agriculture backward to industry and services. In addition, India’s energy mix continues to be dominated by coal because it is still making the transition to renewables. The slower transition to clean energies, along with rapid urban growth and population increase, may delay the EKC turning point and consistently affect what the normal income-emissions trajectory is. Apart from the inverted U-shaped trajectory traces being evident in [Ayhan et al.,’s \(2023\)](#) study, findings on Russia, South Africa, Brazil, and China are congruent with [Aye and Edoja’s \(2017\)](#) highly concentrated manufacturing companies. Besides, CO₂ emission variations in Brazil, Russia, China, and South Africa are likely to result from the presence of energy-intensive industries (e.g., mining and manufacturing) relying heavily on fossil fuels. In the presence of increasing GDP, these industries increase their output, resulting in higher energy consumption and, consequently, an increase in carbon emissions. An increase in economic activity in these countries may increase CO₂ emissions if the energy mix is dominated by coal and other carbon-intensive sources. Most importantly, rapid economic growth often

necessitates increased infrastructure development, which may involve energy-intensive construction projects. With a GDP cumulative effect on CO₂ emissions of 0.159, aligning BRICS economies’ rapid industrialization and economic growth initiatives with environmental management policies targeted at reducing CO₂ emissions is highly coveted in BRICS economies. Essentially, this confirms [Aye and Edoja’s \(2017\)](#) notion that GDP growth levels over 0.156 always result in higher CO₂ emissions. Consequently, this raises an environmental alarm as it signals that the BRICS’s initiatives to boost economic performance will adversely impact the environment through a surge in CO₂ emissions. Therefore, the need for BRICS economies to adopt renewable energy, energy efficiency, and sustainable development policies cannot be refuted in this context. Such findings also signal the importance of increasing cleaner technologies and shifting toward cleaner energy sources, reducing the economic activities’ carbon intensity. Since traces of ITP evidence have been lacking, our findings add traction to the long-standing energy consumption and CO₂ emissions debate by establishing a GDP-related ITP of -0.40 for BRICS economies. Amid such discoveries, there is a policy case for early investments in renewable energy sources involving the promotion of energy efficiency measures, implementation of carbon pricing mechanisms, and incentivizing renewable energy projects. Secondly, the study findings project that an all-size-fits-all renewable energy consumption policy across BRICS economies is effective in abating CO₂ emissions in Russia, South Africa, China, and Brazil by 47%, 32%, 8%, and 6%, respectively, as opposed to a 13% increase in CO₂ emissions observed in India. Hence, this study obtained good results and agreed with

the empirical investigation of [Al-Mulali and Ozturk \(2016\)](#), which found a reduction in CO₂ emissions of 12% and 4%, respectively. As a result of the implementation of renewable energy consumption policies, these results are not surprising. Therefore, this study's insights can also prove to be an effective solution to low- and middle-income countries and the MENA region's long-standing environmental issues. Meanwhile, this reduction can, therefore, be attributed to the successful integration and adoption of renewable energy sources in Russia, possibly driven by favourable policy shifts in technological advances or energy production. Although South Africa may have developed effective renewable energy policies aimed at transitioning from carbon-intensive energy sources, China's reduction, even though relatively small, may reflect a shift towards cleaner energy sources and significant investments in renewable energy infrastructure. By successfully implementing policies related to renewable energy, Brazil, with its emphasis on hydropower and bioenergy, may have experienced a reduction in emissions. In the case of India, rapid population growth and urbanization may have outpaced renewable energy policies positive effects. In light of the disparity in outcomes, it is crucial to understand and address the factors that influence CO₂ emissions. Thus, to achieve policy success, it is imperative to consider factors specific to each country, such as economic structures, policy implementation, and energy infrastructure. BRICS countries may require policymakers to tailor policies on renewable energy consumption in response to their specific needs and challenges. Thirdly, with an observed net elastic carbon pricing policy effect of 1.387, CO₂ emission increments observed in China ($\beta_{44}=1.10^*$), South Africa ($\beta_{45}=0.79$), and India ($\beta_{43}=0.07$) outweigh CO₂ emission reductions observed in Brazil ($\beta_{41}=-0.35$) and Russia ($\beta_{42}=-0.22^*$) for each marginal price increase of \$1/tCO₂. Consequently, this not only suggests ineffectiveness in BRICS economies' adoption of carbon pricing policies but also highlights the importance of exploring the potential transferability and adaptability of successful policies across BRICS nations. Despite China's keen pursuit of various strategies to reduce CO₂ emissions from its coal-dominated electric power system ([Li et al., 2022](#)), its carbon pricing and power market reforms are in their infancy and point to ineffectiveness and

potentially unintended effects in reducing its coal-dominated electric power system. Accordingly, a higher carbon tax may not cause significant reductions in CO₂ emissions due to incomplete coverage of emissions sources and a subset of industries, especially in sectors with elastic demand. In low and middle-income countries like South Africa and India, equity concerns loom large ([Steckel et al., 2021](#)). Consequently, public support of domestic climate and energy policies is severely undermined. It is often the case that policies that increase the price of fossil fuels, which in turn increase the price of essential energy services, are met with fierce resistance from the public. On the contrary, Brazil and Russia have economies that are heavily reliant on natural resources, particularly in the form of fossil fuels (oil and gas in Russia, and agriculture and deforestation-related activities in Brazil). Hence, the implementation of carbon pricing policies could encourage the adoption of cleaner technologies and practices, leading to emissions reductions. On a sectoral level, vulnerable sectors should be supported to move towards carbon-friendly production processes and materials. Policymakers should carefully consider a complex interplay of global market dynamics, technological considerations, political factors, policy design and economic structures when designing and implementing carbon pricing policies to ensure positive environmental outcomes while fostering economic development. Lastly, although financial development inelastically curbs CO₂ emissions in BRICS economies by -0.273, the findings show that a 1-unit improvement in India and China's financial development levels dampens environment preservation initiatives by increasing CO₂ emissions by 0.10t and 0.11t, respectively. [Xu et al., \(2021\)](#) echoed similar sentiments by postulating that financial development's impact on CO₂ emissions changes from negative to positive as industrialization and energy consumption increase. The findings also support financial development's role in abating CO₂ emissions in Brazil, Russia, and South Africa by 5%, 25%, and 19%, respectively. Such findings mirror [Khan and Ozturk's \(2021\)](#) findings that support the pollution-inhibiting role of financial development in 88 developing countries during the 2000-2014 period. Interestingly, this study suggests that varying financial regulations and incentives related to

carbon taxes, green financing, or sustainable investments can affect how financial development impacts emissions. On a policy level, Brazil, Russia, and South Africa's financial development policies can be utilized to incentivize and stimulate green innovation and emission reductions, and influence sustainable development. Besides, South Africa, Russia, and Brazil have diverse industrial structures and energy profiles compared to India and China. They might have less energy-intensive industries or greater reliance on renewable energy sources, which could be less carbon-intensive. This study analyzes total CO₂ emissions across the BRICS economies, and it does not break CO₂ emissions down by sector (e.g. transport, industry, residential). This study allows us to see the overall trends in the environment, but it loses the sector specific EKC relationships which probably differ by sector depending on the sector structure and energy use. Future studies could disaggregate emissions, to illuminate the fact that EKC relationships are often heterogeneous across and within sectors. Moreover, the effectiveness of environmental policies within the EKC perspective may be substantially moderated by differences in institutional capacities and governance structures unique to each country. In BRICS countries, differences in regulatory compliance, transparency, and the processes of policy action may impact the trajectory and timing of achieving emissions reductions. Countries with more robust institutional frameworks may have a clearer path in developing and executing effective renewable energy and carbon pricing policies leading to an earlier EKC turning point. Future work should continue to unpack the institutional dimensions of environmental policy outcomes, identified in our scope, across emerging economies.

CONCLUSION

The manuscript disentangled and shed light on the intricate dynamics of carbon pricing policies, renewable energy consumption, economic growth, and financial development's effect on CO₂ emissions and their implications for sustainable development in BRICS countries. A multi-country ARDL approach was conducted using 1990 to 2022 data to validate claims that panel data estimations rely on an unsubstantiated similar characteristics. Several important policy options have been advanced to

design an environmental strategy that can reduce the level of CO₂ emissions. The research provides theoretical foundations for understanding whether BRICS economies follow the suggested inverted U-shaped curve or diverge from it by examining the trajectory of CO₂ emissions concerning economic growth. Apart from providing theoretical insights into designing long-term sustainable development policies in BRICS economies concerning CO₂ emissions, the EKC hypothesis enables cross-country comparisons and offers regional policy implications. The study provides policymakers with valuable insights to enhance renewable energy adoption and reduce carbon emissions. Further research and policy measures should build upon these findings to ensure sustainable and environmentally responsible development within the BRICS initiative. The study is not void of limitations, and the major limitation is the lack of comparative analysis, as a multi-country ARDL analysis overlooks shared regional dynamics and restricts the ability to compare interactions, patterns, and trends among BRICS nations. In addition, by not capturing cross-country effects, the study may overlook influences of economic and policy changes or spill-over effects in one BRICS country on others. As a result, this can hamper efforts to enhance understanding of how policy interventions interact across countries. Therefore, future studies should integrate cross-country comparisons with country-level analysis to gain a more comprehensive understanding of differences, similarities, and regional dynamics among BRICS countries. To chart the course of financial development, economic growth, and policy interventions in BRICS countries, panel longitudinal studies and time-series analyses can be conducted. As this study discusses renewable energy use, carbon pricing, and financial development as the primary influences behind emissions trajectories, this still does not account for trade openness, foreign direct investment (FDI), and overall global economic integration as potential contributors. These other factors could all potentially alter emissions trends, and BRICS countries are particularly reliant on international trade and investment flows. Follow-up studies could expand the model in this research to include some of these variables to investigate their behavior when interacting with renewable energy use and emissions reductions. Although this study

has focused on macroeconomic and policy-driven determinants of CO₂ emissions, it is recognised that aspects of socio-demography, including urbanization, population growth or decline, and income inequality, may serve significant mediating effects on the growth-emission relationship. These narratives of urbanization, population growth, population decline, and income inequality will shape consumption patterns, energy demands, and the ability to access sustainable infrastructure, and hence they to also be predictors of emissions in future analyses. Additionally, political stability, institutional quality, and governance structures can shape the efficacy and timing of environmental policy implementations. In some contexts, these issues can affect when and where the Environmental Kuznets Curve turning point occurs for BRICS countries. While these institutional and demographic aspects of sustainability are beyond the capability of the present model, they represent the important aspects of future potential research to investigate the complex and country-level specific pathways towards sustainable development. Furthermore, this study does not use a regional clustering method with BRICS. However, comparing groupings such as Russia–China or India–South Africa may yield different EKC trends resulting from geographic, economic, or policy similarities. Future research may wish to investigate clustering to yield more directed policy implications.

AUTHOR CONTRIBUTIONS

M. Kamal: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization. The author has read and agreed to the published version of the manuscript.

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None

CONFLICT OF INTEREST

The author confirms no conflicts of interest and fully complies with ethical standards, including consent, plagiarism, and publication practices.

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ABBREVIATIONS

\$	United States Dollar
ADF	Augmented Dickey-Fuller
ARDL	Autoregressive Distributed Lag
BRICS	Brazil, Russia, India, China, and South Africa
CE	Carbon Emissions
CO ₂	Carbon Dioxide
CPP	Carbon Pricing Policy
DOLS	Dynamic Ordinary Least Squares
EKC	Environmental Kuznets Curve
EPSI	Environmental Policy Stringency Index
EU	European Union

FD	Financial Development
FMOLS	Fully Modified Ordinary Least Squares
GDP	Gross Domestic Product
GMM	Generalized Methods of Moments
ITPs	Income Turning Points
MENA	Middle East and North Africa
OLS	Ordinary Least Squares
PMG-ARDL	Pool Mean Group-Autoregressive Distributed Lag
PP	Phillips Perron
PVAR	Panel Vector Autoregression
REC	Renewable Energy Consumption
UNFCCC	United Nations Framework Convention on Climate Change
VECM	Vector Error Correction Model

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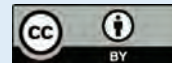
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ORIGINAL RESEARCH PAPER

Application of Game Theory in solving the nuclear waste treatment conflict between countries using ϵ -MOEA

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ABSTRACT

BACKGROUND AND OBJECTIVES: The management of high-level nuclear waste is a pressing global challenge, with over 400,000 metric tons in temporary storage worldwide. International disputes frequently arise due to disagreements over site selection, cost allocation, environmental risks, and long-term liability, often leading to negotiation deadlocks. Existing governance frameworks lack structured mechanisms to balance the competing objectives of multiple stakeholders, including waste-producing ("Disposer") nations and potentially affected ("Affected") nations. This paper aims to resolve these transboundary nuclear waste treatment conflicts by developing a hybrid analytical model that integrates Game Theory to model strategic interactions and the ϵ -Multi-Objective Evolutionary Algorithm (ϵ -MOEA) to find optimal solutions that balance competing goals such as cost, environmental safety, and economic benefits.

METHODS: This manuscript employs a combined Game Theory and computational algorithm approach to resolve international nuclear waste disputes. Game Theory models the conflict between two player types: disposer countries (waste producers) and affected countries (those impacted by disposal). Each player has specific goals, strategies, and costs, with the model seeking a Nash Equilibrium—a stable agreement where no country can unilaterally improve its outcome. Due to the problem's high complexity with multiple competing objectives, the study utilizes the ϵ -MOEA optimization algorithm. This algorithm efficiently explores millions of possible strategy combinations to identify optimal compromises, balancing outcomes to ensure fair and practical solutions for all involved countries.

FINDINGS: Computational experiments compared ϵ -MOEA against other multi-objective algorithms (NSGA-II, NSGA-III, PESA2, VEGA). The key finding was that all algorithms converged to the same optimal fitness value (-5280.33), demonstrating the model's robustness in identifying a stable equilibrium. However, ϵ -MOEA achieved this result with the shortest and most stable runtime (approximately 5.00 seconds per iteration), significantly outperforming other algorithms in computational efficiency. This indicates that ϵ -MOEA is particularly well-suited for solving this complex, high-dimensional problem efficiently, providing a diverse set of Pareto-optimal solutions for policymakers to evaluate trade-offs.

CONCLUSION: A hybrid Game theory and ϵ -MOEA framework effectively resolves international nuclear waste conflicts by modeling strategic interactions and optimizing for multiple objectives. This scalable approach identifies stable, fair agreements that balance the interests of both producing and affected nations, supporting sustainable international governance. Future work should focus on improving computational efficiency for larger numbers of players.

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INTRODUCTION

Managing high-level nuclear waste remains one of the most pressing and unresolved challenges in global energy and environmental policy. Despite decades of research and international regulation, no universally accepted, large-scale, long-term solution exists, leaving over 400,000 metric tons of spent nuclear fuel in temporary storage as of 2023 (Sjöberg & Sjöberg, 2009). The central challenge lies less in technical feasibility than in the political, economic, and ethical barriers to implementation. Countries differ in geological conditions, technological capacity, and public acceptance, leading to divergent national policies and regulatory approaches. Domestic disposal may be infeasible for nations with limited territory or unstable geology, pushing the issue into the international arena. However, proposals for shared or transboundary repositories often trigger fierce resistance from potential host countries and neighboring regions, due to concerns about sovereignty, environmental justice, and long-term liability (World Nuclear Association, n.d.; International Atomic Energy Agency, 2019). This persistent deadlock—illustrated by the European Union’s failure to establish a joint deep geological repository despite technical readiness—underscores the systemic gap: the absence of transparent frameworks to balance competing stakeholder interests. The long-term structure of the IAEA Safety Standards Series is illustrated in Figure 1. The asymmetric distribution of benefits and risks further exacerbates these disagreements. Waste-producing countries may seek cost-efficient disposal abroad,

while host countries demand compensation, security guarantees, and environmental safeguards. As a result, international negotiations frequently stall, leaving waste stockpiled in interim storage facilities that were never designed for multi-decade use (Yue et al., 2017). A notable example is the decades-long deadlock in the European Union over a shared deep geological repository, where competing interests have blocked progress despite clear technical feasibility (Li & Wang, 2023). Similar conflicts have emerged in East Asia and North America, highlighting a systemic gap in current governance frameworks: the absence of structured, transparent mechanisms to balance competing stakeholder objectives.

Addressing this gap requires tools that can model conflict, cooperation, and trade-offs simultaneously. Research into sustainable alternatives, such as transmutation, waste reuse, and deep geological repositories, must be balanced with interim storage in strategic approaches to nuclear waste management (International Atomic Energy Agency, 2019). Game Theory (GT) provides a foundation for analyzing strategic interactions, fostering collaboration, and stabilizing international agreements (Köksalan et al., 2011; Yu et al., 2020). It assists in reducing conflicts and coordinating national incentives by encouraging stable agreements (Ho et al., 2022). A fundamental idea in GT, the Nash equilibrium allows stakeholders to make logical decisions (Finus & Rundshagen, 2015). Yet, Game theory alone cannot account for the multiple conflicting objectives—cost, safety, environmental impact—that define nuclear waste man-



Fig.1: The long-term structure of the IAEA Safety Standards Series (International Atomic Energy Agency, 2019)

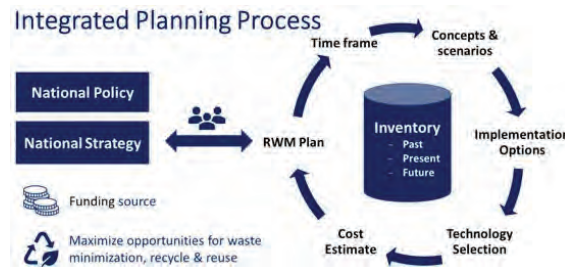


Fig. 2: Flow sheet diagram of an integrated planning process (Zoran et al., 2022).

agement. To address this, this study integrates Game theory with the ϵ -MOEA. ϵ -MOEA is designed to generate diverse Pareto-optimal solutions through ϵ -dominance, enabling decision-makers to explore trade-offs efficiently (Wong et al., 2017). Its capacity to maintain various solutions appropriate for multiple national agendas accounts for its efficacy in resolving nuclear waste issues (Yang & Xu, 2021). The algorithm employed in this study, ϵ -MOEA (Epsilon Multi-Objective Evolutionary Algorithm), is a type of Multi-Objective Evolutionary Algorithm (MOEA) that uses ϵ -dominance to maintain a diverse set of Pareto-optimal solutions. According to (Wong et al., 2017), the Pareto front generated by MOEAs allows decision-makers to explore trade-offs and make informed decisions based on stakeholder preferences. ϵ -MOEA is an optimization technique that considers multiple conflicting objectives simultaneously, utilizing Pareto front solutions, constraints, and ϵ -dominance to define acceptable trade-offs. A study by Yang & Xu (2021) demonstrated that ϵ -MOEA outperformed other interactive MOEAs due to its efficient handling of ϵ -dominance. This algorithm is particularly beneficial in nuclear waste treatment disputes, where it is crucial to balance cost, safety, and environmental impacts among the increasing number of involved countries. In a multi-stakeholder context, ϵ -MOEA retains a wide range of solutions tailored to the diverse strategies and preferences of different nations. Fig. 2 depicts the flow sheet diagram of an integrated planning process.

Addressing the conflict related to nuclear waste treatment among countries involves several critical inquiries and challenges:

- (i) How can MOEAs balance competing goals and optimize the distribution of nuclear waste sites?
- (ii) In what ways can Game Theory support the creation of just and effective waste management

plans?

(iii) In international negotiations, what function does strategic interaction modeling serve?

By addressing these questions, the study contributes a hybrid analytical framework that combines optimization and strategic modeling, with the potential to guide international institutions, like the IAEA, toward more sustainable and cooperative solutions. As the summary is illustrated in Table 1, conflicts over nuclear waste treatment have been extensively studied, with research providing insights into mitigation strategies. This section reviews key contributions, highlights unresolved challenges, and demonstrates how our approach addresses existing gaps. Game theory has emerged as a critical tool in analyzing international cooperation on nuclear waste management, mitigating non-cooperative behavior while identifying incentives for collaboration (Grimes-Casey et al., 2007). (Kaushal & Nema, 2013) examined its role in optimizing disposal strategies, emphasizing leadership dynamics in transboundary waste governance. Other studies have explored cooperation mechanisms: (Phathanapirom et al., 2020) analyzed optimal collaboration levels in the nuclear fuel cycle, while (Finus & Rundshagen, 2015) assessed the stability of scientific agreements. Additionally, strategic decision models offer alternative conflict-resolution approaches. Beyond cooperative modeling, strategic decision frameworks provide alternative perspectives on conflict resolution (Xu et al., 2022), modified the Prisoner's Dilemma to optimize national benefits, and Phathanapirom et al. (2020) developed a financial model balancing national interests. (López-Cabarcos et al., 2024) underscored the role of trust and reputation in sustaining long-term agreements. However, these approaches remain largely single-dimensional, focusing on either political cooperation or economic trade-offs, without simultaneously accounting for

Table 1: Summary of recent related research papers by approaches and algorithms.

Method	Year	Problem
GT	2017	Analyze the effect of international law (Schwenk-Ferrero & Andrianov, 2017)
GT	2021	Solve the problem of the spent nuclear fuel treatment process (He <i>et al.</i> , 2021)
GT, GMCR	2022	International cooperation in nuclear waste disposal (Yang & Xu, 2021)
GT	2022	Optimize nuclear waste, minimizing potential harm to the environment and humanity, and achieving sustainable development (Xixi <i>et al.</i> , 2022)
GT, NE	2021	Develop equitable solutions when bargaining over nuclear waste treatment (Darda <i>et al.</i> , 2021)
GT	2020	Optimizing nuclear fuel cycle transitions that incorporate (Eryganov <i>et al.</i> , 2020).
GT	2022	Optimize international cooperation for ensuring safety, security, and non-proliferation (Kaushal & Nema, 2013)
GT, NE	2021	Policy about marine environments under the current situation (Qu <i>et al.</i> , 2018)
GT	2020	Developed to assess the costs and advantages of ultimate repository protection (Ju <i>et al.</i> , 2020)
GT	2022	Help countries maximize benefits from NWM while minimizing costs (Xu <i>et al.</i> , 2022)
GT	2020	International cooperation in nuclear waste disposal (International Atomic Energy Agency, 2020)
GT	2019	Find efficient NWM (Handl, 1981)
GT, NE	2019	Solve nuclear disposal conflicts in the construction contract (Montonen <i>et al.</i> , 2019)
GT	2019	Find the balance point of the stakeholder's benefits (Li & Wang, 2023)
GT	2020	Investigate and resolve the uncertainty on nuclear waste disposal costs (Finus & Rundshagen, 2015)

environmental risks, geopolitical tensions, and long-term sustainability. recent studies (e.g., Xu *et al.*, 2022; López-cabarcos *et al.*, 2024) have introduced more realistic elements such as dynamic strategy adjustments and trust mechanisms, yet these still lack robust multi-objective optimization frameworks. In contrast, our study differentiates itself by integrating the ϵ -moea algorithm into a game-theoretic framework. this combination allows the simultaneous optimization of political, economic, and environmental factors, creating a more holistic approach to resolving international nuclear waste conflicts. Despite these advancements, existing models often lack multi-objective optimization frameworks that address political, environmental, and economic factors concurrently. By integrating the ϵ -MOEA algorithm into a game-theoretic framework, our study bridges this gap, providing a more comprehensive approach to resolving international nuclear waste conflicts.

With an emphasis on safety and security, the method improves repository design and operation while taking cultural, political, and economic concerns into consideration. By considering factors like long-term health hazards, environmental harm, and intergenerational equality, the GT model ensures that stakeholders make balanced decisions. Stakeholder

issues are addressed by optimizing nuclear waste disposal using a combination of Game theory and the MOEA framework. The ϵ -MOEA model balances environmental effects, transportation costs, and safety to determine the best storage places. Offering insights on fair and effective methods for disposing of radioactive waste aids in studying international policy. Through effective policymaking and collaborative tactics, the platform seeks to support international efforts to reduce the hazards associated with nuclear waste.

MATERIALS AND METHODS

The management of Nuclear Waste Treatment (NWT) is a complex issue influenced by conflicts of interest and cost reduction. The distribution of resources and waste treatment technology significantly impacts outcomes and goals. A Game-theoretic framework is needed to analyze strategic interactions and negotiation dynamics in international agreements. Therefore, our topic can be a model. Assuming that we have $\in N^*, n > 2$ players, all of which are countries from around the world. These players can be categorized into 2 specific types of players: m ($m \in N^*, n > m > 1$) players that are type d represents Disposer countries and

l ($l \in N^*, n > l > 1$) players whose type is a represents the affected countries. For instance, we consider three countries: the USA, Russia, and China, all facing the complex challenge of disposing of their nuclear waste. Each country has a set of core objectives, with minimizing *environmental impact* (E), reducing *cost*, maximizing *preferences* (P), and minimizing *risk* (R) being at the forefront. To illustrate, let's assume a dataset with specific values for each country's objectives as per Table 2.

The example data presented in Table 2 are hypothetical values constructed for illustrative purposes rather than direct measurements from real-world nuclear waste disposal projects. They are intended to demonstrate how the proposed game-theoretic and ϵ -MOEA framework can be applied to compare countries with different characteristics. By clarifying these assumptions, we emphasize that the table serves as a conceptual illustration to explain the mechanics of the unified game model. In future empirical applications, the framework can incorporate real-world data such as nuclear policy indicators, economic costs, and environmental risk assessments. In the problem of solving conflicts between countries, our research aimed at two types of players with different characteristics: nuclear waste-disposing countries and affected countries. The two kinds of players share some similar characteristics, such as economic benefits (Finus & Rundshagen, 2015), environmental benefits, environmental damage (Yue et al., 2017), and economic

cost for solving the problem (Finus & Rundshagen, 2015). In addition, influenced countries have one more characteristic: health benefits when reducing nuclear waste impact (Li & Wang, 2023). For nuclear waste-producing countries, key variables include the daily discharged wastewater volume (m^3/day), disposal duration (days), human and environmental benefits ($\$/day$), and disposal costs ($\$/day$). For affected countries, relevant factors are the received wastewater volume (m^3/day), duration (days), compensation received ($\$/day$), and risk mitigation costs ($\$/day$). About the strategies, we consider 4 general strategies for both types of players: The impact of nuclear waste discharge on the environment, the cost per nuclear waste discharge event, the impact of nuclear waste discharge on health, and the last one is the risks associated with nuclear waste discharge. The flowchart of the solution for the NWT problem using ϵ -MOEA is illustrated in Fig. 3. The characteristics of players and strategies are shown in Table 3.

The study explored safe nuclear waste disposal by considering stakeholders' interests, including waste-producing countries, neighboring countries, international organizations, and residents. Solutions include domestic treatment, environmental release, acceptance by neighbors, and setting fees. A stable equilibrium point is crucial, and concerns can be resolved through negotiation. International organizations set requirements for radioactive substance concentrations. Game theory helps understand trade-

Table 2: Summary of data on amending nuclear waste disposal [32]

Country	E (1-10)	C (USD)	P (1-10)	R (1-10)
America	4	1,200	6	2
Russia	5	1,300	5	3
China	3	1,000	8	1

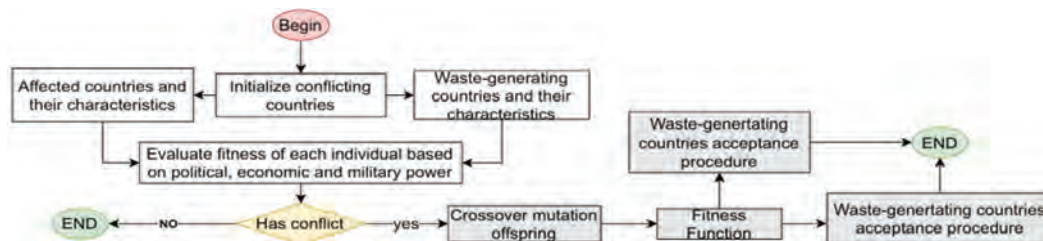


Fig. 3: Flowchart of the solution for the NWT problem using ϵ -MOEA

Table 3: Characteristics of players and strategies.

Types of players	Characteristics of a Player	Characteristics of Strategies
Disposer d	q^d : Quantity of nuclear waste	BH^{da} : Benefits for humans
	t^d : Discharge period	BE^{da} : Benefits for the environment
	m : Total number of players d	C^{da} : Cost has to pay
	q^a : Quantity of nuclear waste received	MR^{ad} : Money received
Affected a	t^a : Waste reception period	RP^{ad} : Potential Risk
	l : Total number of players a	

offs and potential conflicts. The unified game-based model (Trinh et al., 2019) is a framework that integrates game elements to design a generic model for many sorts of Game theory. Solving conflicts in NWT is a class of conflict problems that belongs to the type of cooperative game with non-zero-sum and imperfect information. Therefore, the Unified Game-based model (Trinh et al., 2019) is necessary and possible to provide efficient solutions or strategies for the above-mentioned problems.

$$G = \langle \{P^d, P^a\}, \{S^d, S^a\}, \{u^d, u^a\}, R^C \rangle \quad (1)$$

Let G represent the unified game model. The set $P^d = \{p_1^d, \dots, p_m^d\}$ denotes the nuclear waste-disposing countries, while $P^a = \{p_1^a, \dots, p_l^a\}$ denotes the countries that are affected by waste disposal. Each country in these sets is considered as an individual player with its own characteristics (e.g., resources, political priorities, and environmental sensitivities). The strategy spaces for the t groups are given by $S^d = \{S_1^d, \dots, S_x^d\}$ for the disposing countries and $S^a = \{S_1^a, \dots, S_y^a\}$ for the affected countries. In practical terms, these strategies might represent options such as choosing a disposal method, negotiating for compensation, or forming alliances. The payoff functions $u^d: S^d \rightarrow \mathbb{R}$ and $u^a: S^a \rightarrow \mathbb{R}$ measure the outcomes for each player. For example, disposing countries may maximize cost efficiency or political leverage, while affected countries may focus on minimizing environmental risk or maximizing compensation. Finally, let R^C be a vector space representing the conflict set C . A nonempty vector $v_{-} \in R^C$ represents the conflicts among n players ($1 \leq n \leq N$), expressed in the normal (strategic) form of the game. This formulation captures the interplay of competing interests, where

each player's choice directly influences both cooperation and conflict in international nuclear waste management.

The payoff function of Disposer can be calculated by the following:

$$u^d = \sum_{i=1, j=1}^{m, l} q_i^d t_i^d (BH_{ij}^{da} + BE_{ij}^{da}) - \sum_{i=1, j=1}^{m, l} q_j^a t_j^a C_{ij}^{da} \quad (2)$$

Where u^d represents the payoff function of Disposer d . i, j respectively represent the ordinal number of each player. m, l indicate the total number of Disposer d and the total number of Affected a respectively. q_i^d, q_j^a illustrate the quantity of nuclear waste from d and the quantity of nuclear waste received from d of a . t_i^d, t_j^a represent the discharge period of d and the waste reception period of a calculated by day. $BH_{ij}^{da}, BE_{ij}^{da}$ describe the benefits for humans and the environment during the disposal of a quantity q per time t of Disposer d to Affected a . Finally, C_{ij}^{da} is the Cost that d has to pay to a during the disposal of quantity q per time t . The payoff function of the Affected can be calculated by the following:

$$u^a = \sum_{i=1, j=1}^{m, l} t_j^a q_j^a MR_{ji}^{ad} - \sum_{i=1, j=1}^{m, l} RP_{ji}^{ad} q_i^d t_i^d \quad (3)$$

Where u^a represents the payoff function of Affected a . i, j respectively represent the ordinal number of each player. m, l indicate the total number of Disposers d and the total number of a respectively. q_i^d, q_j^a illustrate the quantity of nuclear waste from d and the quantity of nuclear waste received from d of a . t_j^a, t_i^d represent the discharge period of d and the waste reception period of a calculated by day. MR_{ji}^{ad} refers to the amount of money a received from d countries to process quantity q of nuclear

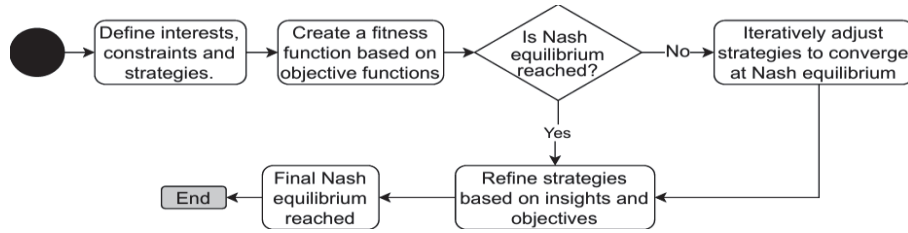


Fig.4: Flowchart of solving the unified Game-based model

waste per time t . Finally, RP_{ji}^{ad} are the potential risks or costs a incurred from relying on d countries for waste disposal. A special framework for comprehending and maximizing interactions among stakeholders in nuclear waste across nations is provided by the Game theory model. Thus, specifically considering each stakeholder's strategic decision-making, possible collaboration, and conflict. By using the NE formula, the discharging country can determine the strategic discharge amount to maximize profits based on other factors such as radioactive dilution and compensation if problems occur. To address NWT problems between countries, the Unified Game-based model can be applied by outlining how the algorithm could be implemented. Determining the parties' goals, limitations, and tactics is the first step. It also recommends developing a fitness function based on two objective functions: u^a and u^d . The model looks for an NE where all parties' aggregate utility is maximized. Strategies are refined iteratively until they converge to a balanced state where no player can increase their payout unilaterally. Figure 4 shows the flowchart for solving the Unified Game-based model.

NP-hard problems are problems that the computer cannot find the exact optimal solution in polynomial time (Montonen et al., 2019). NWT is an NP-hard problem with a high-dimensional decision space, intrinsic uncertainty, and a combinatorial character. Long-term consequences are complicated by waste treatment, technology, legislation, and geopolitics. These uncertainties may be modeled with the use of probabilistic techniques and scenario analysis. Resource limitations make the problem worse. ϵ -MOEA provides a variety of Pareto-optimal results, objective balance, and effective exploration. The ϵ -MOEA approach is employed to address the

multi-objective optimization problem arising from the application of Game theory in resolving conflicts between countries regarding NWT. In this scenario, we can identify the strategies for the nuclear waste-disposing country, the influenced country, and represent them as chromosomes. An example is shown in Fig. 5.

Where the chromosome encodes a string of strategies, where each player's strategy is represented by their respective gene. The value of the gene indicates the specific strategy chosen by the player. Here, the value 0 signifies the absence of a strategy choice, while values 1, 2 denote specific types of strategies selected by the players. Furthermore, it always yields the same result for the same input. It should also be scalable and computable. Here's how we apply the fitness function:

$$F = \left| \frac{\sum_{i=1}^m u_i^d}{m} - \frac{\sum_{j=1}^l u_j^a}{l} \right| \quad (4)$$

Where F is the problem's fitness function. i, j respectively represent the ordinal number of each player. m, l indicate the total number of d and the total number of a respectively. Finally, u_i^d, u_j^a respectively indicates the payoff function of d and a . To find a solution with the optimal F , the ϵ -MOEA algorithm has been proven to be one of the most effective algorithms available. It evaluates various solutions along the Pareto front, balancing environmental impact, economic costs, and resource allocation. Figure 6 illustrates a flow chart of the ϵ -MOEA Process for NWM decision-making, and Fig. 7 depicts pseudo-code for NWT.

The algorithm starts by creating a large initial population of alternatives for treating radioactive waste, assessing their effects on the environment, legal system, and economy, and grouping people into

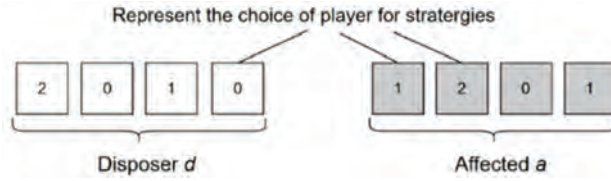


Fig. 5: The process of selecting pairs of chromosomes

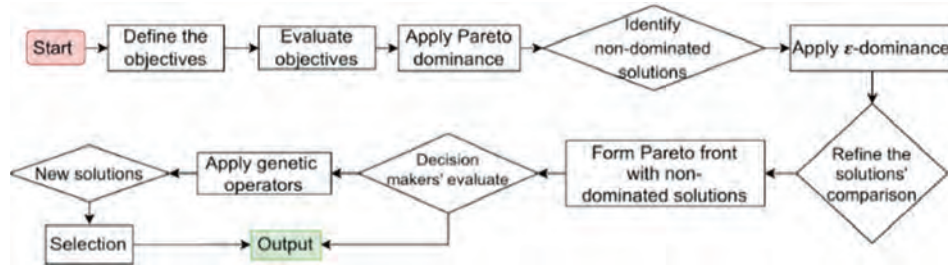


Fig. 6: A flow chart of the ϵ -MOEA Process for NWM decision-making.

Algorithm 1 Multi-Objective Evolutionary Algorithm (E-MOEA)

```

1: Main E-MOEA Algorithm main_cmoa
2: population  $\leftarrow$  initialize_population
3: for generation  $\leftarrow$  1 to max_generations do
4:   evaluate_individuals(population)
5:   fronts  $\leftarrow$  non_dominated_sort(population)
6:   for each front in fronts do
7:     crowding_distance(front)
8:   end for
9:   selected_parents  $\leftarrow$  select_parents(population)
10:  offspring  $\leftarrow$  crossover_and_mutation(selected_parents)
11:  evaluate_individuals(offspring)
12:  combined_population  $\leftarrow$  population + offspring
13:  population  $\leftarrow$  combined_selection(combined_population)
14: end for
15: return non_dominated_solutions(population)    ▷ Return final Pareto front

```

Fig. 7: Pseudo code for NWT

non-dominated fronts. The crowding distance calculation ensures diversity, and the next generation's parents are selected based on their rank and crowding distance.

RESULTS AND FINDINGS

This section presents the results of comprehensive computational experiments evaluating the effectiveness of the proposed Game theory and ϵ -MOEA model using the experiment parameters listed in Table 4. The system will be written using Java and IntelliJ IDEA for stability and credibility. The exper-

iments will be executed on a robust cloud computing platform supported by Amazon, providing powerful scalability. The server configuration used has a CPU speed of 2.6GHz, 16384 GB RAM, and 300 GB Enterprise SSD storage.

Total number of core objectives that have been applied: 5. Including economic benefit gains for the disposer, financial cost associated with waste disposal for the disposer, environmental cost for the disposer, financial cost of the affected, and environmental cost of the affected. Each player has four crucial collaboration and nuclear waste reduction tactics, and

Table 4: The experiment parameters.

Parameters	ϵ	Range	Rates	Generations
Description	[0.01, 0.1]	1000	80% / 1%	100

Table 5: Sample data of the core objectives of several 5 players.

Players	Core Objectives				
	$p1$	$p2$	$p3$	$p4$	$p5$
Japan d	5987	1854	679	3748	3687
	6709	1546	617	2585	3865
	5670	1768	568	2874	3594
	5760	1754	896	3785	4987
	5789	1768	789	3746	3587
China a	5708	1647	765	3374	4875
	6098	1876	874	2748	3498
	6745	1978	637	2598	4786

Table 6: Comparison of Fitness value across different algorithms.

	NSGA-II		NSGA-III		ϵ -MOEA		PESA2		VEGA	
	Fitness value	Run time (s)	Fitness value	Run time (s)	Fitness value	Run time (s)	Fitness value	Run time (s)	Fitness value	Run time (s)
1	5687,38	6,658	6013,88	6,165	5849,84	5,003	5554,54	5,061	5624,12	6,888
2	5322,94	5,936	5595,02	6,821	5845,94	5,017	5378,3	5,138	5215,68	8,053
3	5738,16	6,023	5902,26	6,303	6010,88	5,008	5449,36	5,07	5497,76	8,011
4	5659,92	5,908	5936,64	7,073	5812,74	5,01	5327,9	5,008	5342,02	7,999
5	5659,36	5,812	5721,12	6,137	5717,28	5,016	5144,08	6,724	5429	8,349

there are probably seven essential traits about variables such as: $p1, p2, p3, p4, p5$ which sequentially represent the characteristics that we have mentioned in our payoff function above. Table 5 provides a comprehensive set of data points that describe various dimensions (environmental impact, cost, preferences, risk) associated with nuclear waste disposal for each player. The data likely serves to evaluate and compare the performance and priorities of each country in handling nuclear waste, which is crucial for developing effective algorithms and strategies for international NWM. In continuation, Table 6 further compares the performance evaluation findings of five distinct multi-objective optimization algorithms, namely NSGA-II, NSGA-III, ϵ -MOEA, PESA2, and VEGA. The primary metrics compared were fitness and runtime.

To compare with the primary algorithm of the study, ϵ -MOEA, four potential multi-objective evolutionary algorithms are used. This comparison can aid in thoroughly evaluating the performance of ϵ -MOEA, diversifying solutions, testing stability, and improving

ϵ -MOEA. It will assist in guaranteeing that the solutions developed for the nuclear waste disposal challenge are optimal and best suited to real-world needs and situations. These data indicate that, while all algorithms could find the best answer, their computing efficiency varied greatly, as shown in Fig. 8 below:

The runtimes of the other two algorithms, NSGA-II and NSGA-III, are nearly identical to PESA2, at 14,32% and 12,49%, respectively. The study demonstrates that all algorithms are capable of solving the problem; however, despite variations in performance, ϵ -MOEA is the most appropriate algorithm because of its optimal fitness value and fast runtimes. The study utilized ϵ -MOEA, an algorithm designed to solve problems with special properties like legally binding goals or safety and environmental risks. The algorithm generated diverse values and performed well in stable and short runtimes. In the 2nd iteration, it completed processing with a shortest processing time of 5.00 seconds, demonstrating its outstanding capability in solving complex problems, such as nuclear waste disposal conflicts. It is acknowledged that

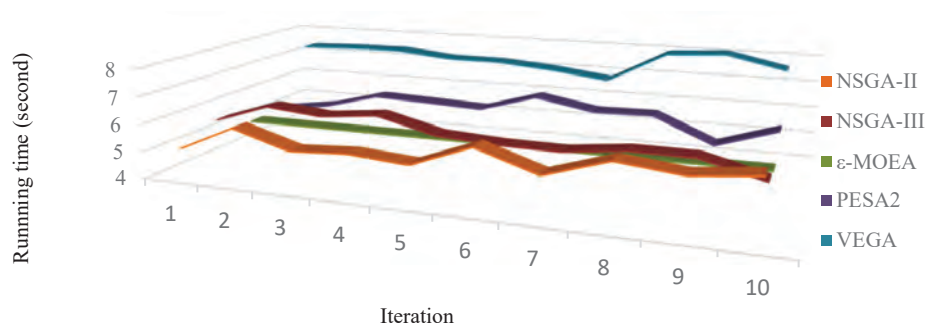


Fig. 8: A comparison of runtimes between different algorithms.

the analysis presented in this study is primarily computational and does not yet incorporate empirical validation through a real-world nuclear waste disposal case study. The purpose of this computational focus was to establish a proof of concept for the proposed ϵ -MOEA-GT framework, ensuring its feasibility, efficiency, and stability under controlled experimental conditions. While this limitation reduces the immediate practical generalizability of the results, it provides a necessary foundation for subsequent research. Future work will extend the framework by applying it to empirical datasets, such as cross-national nuclear waste policies, disposal cost assessments, and environmental risk indices, to test its robustness in real-world contexts. This progression from computational modeling to empirical application will enhance the practical value of the research and strengthen its policy relevance.

CONCLUSION

Nuclear waste treatment disputes remain a persistent challenge in international relations and environmental governance. This study contributes a novel integration of ϵ -MOEA with GT, creating a multi-objective framework that simultaneously incorporates political, environmental, and economic dimensions of nuclear waste management. Unlike previous single-dimensional models, this approach demonstrates how multiple conflicting objectives can be balanced in practice. Empirical findings show that the ϵ -MOEA-GT framework enables more stable cooperative outcomes by reducing incentives for unilateral defection and improving the fairness of burden-sharing among states. Although the algorithm requires longer computation times due to the complexity of

handling multiple actors and objectives, the results indicate that these trade-offs yield more equitable and sustainable agreements. Practically, this model offers policymakers a structured tool to evaluate negotiation strategies, anticipate conflict scenarios, and identify agreements that are both efficient and stable. By directly addressing the interplay of strategic behavior and multi-objective optimization, the study provides a pathway for mitigating international disputes over nuclear waste treatment.

AUTHOR CONTRIBUTIONS

The 1st author contributed primarily to the preparation and writing of the manuscript. Do Thi Ngoc Anh participated in developing the research idea, discussing the model jointly with Dong Trung Anh, and carried out the study under the supervision of Trinh Bao Ngoc. Vu Quoc Huy contributed to dataset collection and field validation. Do Thi Phuong Phuong Thao, Pham Thi Huyen, Ngo Van Quyen, and Hoang Thi Thuy Dung provided financial support that enabled the successful completion of this research.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

ε-MOEA	Epsilon Multi-Objective Evolutionary Algorithm
BE	Benefits for the Environment (in payoff function)
BH	Benefits for Humans (in payoff function)
C	Cost (one of the core objectives)
CPU	Central Processing Unit
E	Environmental Impact (one of the core objectives)
F	Fitness Function
GB	Gigabyte
GMCR	Graph Model for Conflict Resolution
GT	Game Theory
IAEA	International Atomic Energy Agency
MOEA	Multi-Objective Evolutionary Algorithm
MR	Money Received (in payoff function)

NE	Nash Equilibrium
NP-hard	Non-deterministic Polynomial-time hard (a class of computational problems)
NSGA-II	Non-dominated Sorting Genetic Algorithm II
NSGA-III	Non-dominated Sorting Genetic Algorithm III
NWM	Nuclear Waste Management
NWT	Nuclear Waste Treatment
P	Preferences (one of the core objectives)
PESA2	Pareto Envelope-based Selection Algorithm II
R	Risk (one of the core objectives)
RAM	Random-Access Memory
RP	Potential Risk (in payoff function)
SSD	Solid-State Drive
USD	United States Dollar
VEGA	Vector Evaluated Genetic Algorithm

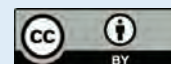
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ORIGINAL RESEARCH PAPER

A modified grey-based decision-making approach to the supplier selection problem for the automobile industry

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ABSTRACT

BACKGROUND AND OBJECTIVES: In the manufacturing sector, selecting the most suitable supplier is a critical strategic decision. In today's context, where sustainability has become a key performance indicator, the automotive industry emphasises supplier selection strategies that align with traditional economic criteria, as well as environmental and social sustainability. Sustainable supplier selection is a complex decision-making process. The objective of this article is to simplify the selection of a supplier, considering all three sustainability factors as important through the expertise of experts.

METHODS: In this study, a grey-based decision-making approach is employed. To address ambiguity and capture subjective judgments effectively, a linguistic scale-based questionnaire is utilized for both supplier evaluation and criteria weight determination. The model converts the expert rating into a grey number-based rating for the criteria weight and the supplier performance rating on each of the identified criteria. The proposed method computes the relative closeness index. The evaluated relative closeness index ranks the best suppliers that are closest to the ideal positive supplier. To demonstrate the applicability and effectiveness of the proposed methodology, a case study from the automotive industry is presented.

FINDINGS: The proposed method employs grey numbers to evaluate the criteria weights and grey numbers for supplier rating. Using modified grey relational analysis, the suppliers are ranked. The criteria identified by the experts were both quantitative and qualitative. The best sustainable supplier is supplier 4, with the relative closeness index farthest from the possibility degree 0.5, with a value of 0.7622. A comparative analysis was conducted, revealing that the top three ranked suppliers demonstrated consistent positions across the evaluated methods.

CONCLUSION: Suppliers from the automobile sector were evaluated using distinct criteria. Industry experts prioritized traditional operational factors such as technical capability, product quality, delivery reliability, workplace safety, and employee health. Furthermore, environmental performance and sustainability were also rated favourably, highlighting the growing importance of environmentally sustainable practices. The study emphasizes the reduction in computational complexity associated with making informed decisions in complex scenarios.

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INTRODUCTION

Supply chain management plays a vital role in an organisation (Gede, 2025). In response to escalating environmental challenges and the global call for sustainable development, organisations are increasingly prioritising environmentally responsible practices across their operations. One critical area experiencing this shift is supply chain management (Wu et al., 2021). Sustainability is achieved through an optimal balance among economic, environmental, and social dimensions, all of which must align with and support the overarching goals of the organization (Afrasiabi et al., 2022). The initial phase in SCM is the selection of appropriate suppliers, a process that necessitates the collective identification and evaluation of relevant environmental, social, and economic criteria by decision-makers (Aslani et al., 2020). Post-pandemic period, purchasing managers have increasingly incorporated Environmental Management Systems (EMS) as a critical evaluation criterion (Govindan et al., 2012). Growing environmental concerns—such as pollution reduction, energy efficiency, and long-term ecological sustainability—have further driven the adoption of Green Supply Chain Management (GSCM) practices within procurement processes (Zimmer et al., 2015). The integration of social and environmental sustainability-related criteria alongside traditional supplier selection parameters is increasingly being aligned with an organization's Sustainable Development Goals (SDGs), often guided by expert input and strategic recommendations (Chauhan et al., 2022). The formulation and execution of strategic supply chain decisions like supplier selection typically involve contributions from multiple stakeholders, reflecting a diversity of professional perspectives and expertise (Shepherd et al., 2024). One of the techniques used by researchers and practitioners from 1970 to date is the Multi-Criteria Decision-Making (MCDM) method, which has been extensively employed across diverse research domains due to its effectiveness in handling complex evaluation problems involving multiple criteria. (Chen & Yang, 2011). Many researchers have supported the use of MCDM in making the right decision in various domains, like employee recruitment selection process using a weighted method and grey relational analysis (Megawaty et al., 2025), in ranking the factors that affect social media marketing in urban cyberspace

(M. Montezarhojat, Y. Vakil Alroaia, A. Rashidi), in selecting a reverse logistics provider in a closed loop supply chain (Khodaverdi & Hashemi, 2015). These methods have proven to be consistently reliable and effective, offering a range of ranked solutions tailored to specific decision-making problems, each reflecting varying levels of significance. This technique helps in selecting the best-ranked supplier among multiple suppliers, evaluating the alternatives, and ranking them. There are various techniques like Analytical Hierarchy Process (AHP), TOPSIS, SAW, MOORA, VIKOR, ELECTRE, GRA, and many more. It is used in many sectors where decision support is needed. Yang & Chen. (2006), Integrated AHP and Grey Relational Analysis (GRA) to develop a method combining the qualitative and quantitative methods to select the best supplier. Eshghizadeh. (2017) used AHP and ANP to estimate the potential of flooding. Research conducted by Kuo et al., (2008) has combined Data Envelopment Analysis (DEA) and GRA for the facility layout and dispatch rules selection problem. The approach is based on Intuitionistic Fuzzy Set (IFS) and GRA to select green suppliers in an uncertain environment. (Bali et al., 2013; Ahmadi et al., 2016) integrated AHP and GRA for the telecom industry to evaluate the sustainable supplier. According to De Oliveira et al., (2023), decision-making could be influenced by decision makers' vagueness, so a Hesitant Fuzzy Linguistic VIKOR (HFLVIKOR) method is used to evaluate the supplier. Ali & Zhang. (2023) proposed Fuzzy Analytical Hierarchy Process (FAHP), Multi-Objective Linear Programming (MOLP), and Fuzzy Compromise Programming (FCP) to understand the economic and environmental aspects, including foreign transportation risk post-COVID in the textile industry. Sudarsanam et al., (2022) integrated expert opinion in criteria weights computed with AI and rated the supplier on seven KPIS; the top ten suppliers are identified for the automobile industry. K.Fahimi et al., (2023) integrated TOPSIS and AHP to construct the organizational excellence model. A review of the existing literature reveals that numerous researchers have proposed various Multi-Criteria Decision-Making (MCDM) methods to facilitate the selection of suitable suppliers. While methods such as the AHP enable comparative evaluation of alternatives, many integrated frameworks combining two or more MCDM techniques have also been developed, which often lead to increased computational complexity.

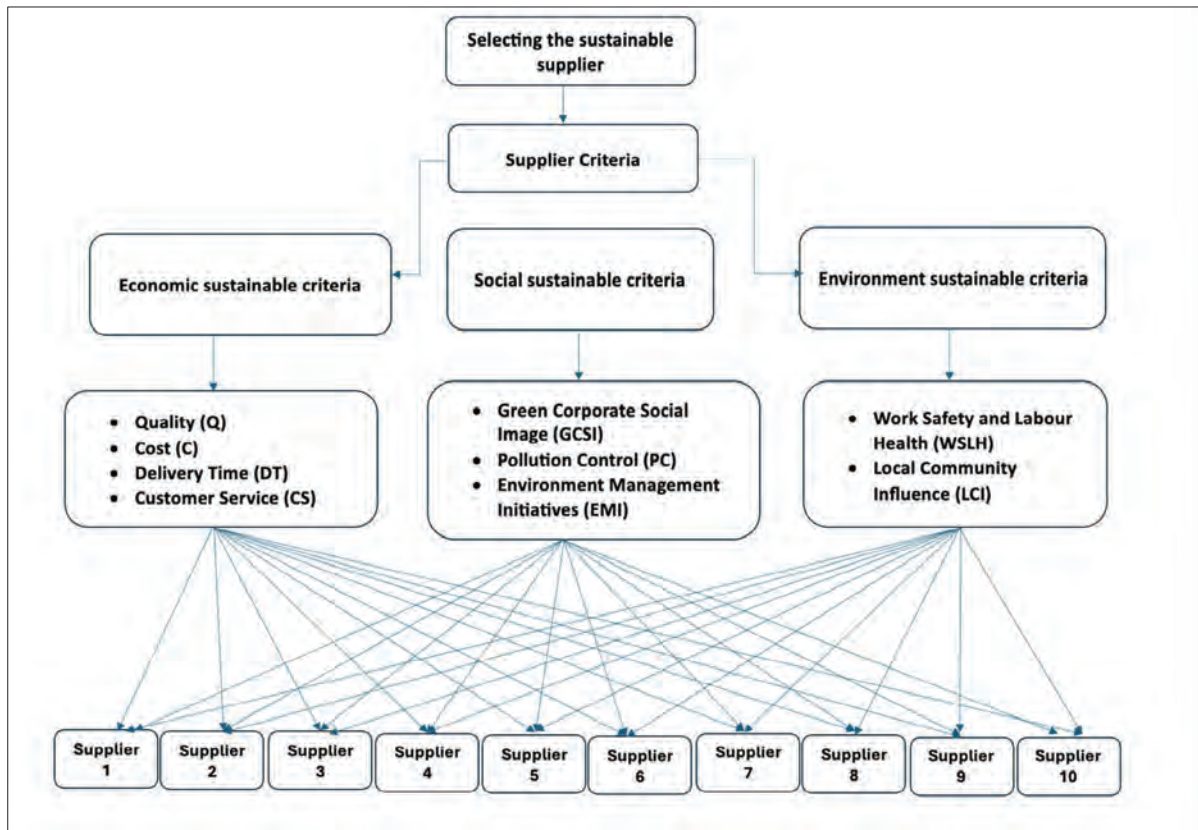


Fig. 2: Proposed Framework for criteria

Although fuzzy set theory has been applied to address uncertainties in decision-making, its implementation tends to be computationally intensive. To overcome these limitations, the present study employs grey set theory, which offers a reduction in ambiguity through the use of linguistic ratings, while also ensuring lower computational effort and greater methodological flexibility. The proposed approach utilises grey-based computation for determining criteria weights and ranking suppliers, thereby providing an efficient and effective supplier evaluation model. In this study, Fig. 1. The framework identifies the most suitable sustainable supplier for the selected industry based on environmental management systems. Relevant criteria for supplier evaluation are determined through expert input and a review of existing literature.

MATERIALS AND METHODS

Study area

The study was conducted on 17th March 2025, in

the renowned automobile industry in Chennai city, Tamil Nadu, India. It is one of the development centres and is engaged in shared development services.

Survey design and data collection

The selection of the most suitable supplier remains a critical aspect of the evaluation process. This study employs expert input to identify relevant selection criteria through direct interviews. A purposive sampling technique is adopted, targeting decision-makers from the supply chain department. To minimize ambiguity in responses, a linguistic scale-based questionnaire is utilised during data collection. The experts evaluate the suppliers based on the criteria they have identified.

Sustainability criteria approach

In 1966, Dickson proposed 23 important criteria in vendor selection, and for a long period, supplier selection has predominantly focused on conventional criteria such as cost, delivery performance, and

Table 1: Sustainable supplier selection criteria

S No	Sustainability Selection	Criteria
1	Economical sustainability	Q C DT TC
2	Environmental sustainability	GCSI PC EMI
3	Social sustainability	WSLH LCI

material quality in economic sustainability. Later research identified various other criteria, like supplier reserve capacity, process capability (Kannan and Tan, 2002), and Technology development (Day, 1994) that would support one of the pillars of sustainability. To achieve social sustainability, an organization must adopt social responsibility in supporting all its stakeholders. Safety regulations for the employees, health concerns, community involvement, and protecting the environment. (Carter and Jennings 2002). This study categorises sustainable supplier criteria into three key dimensions: economic, environmental, and social sustainability. Economic sustainability criteria assess the supplier's capabilities and financial performance. Social sustainability criteria focus on both internal and external social practices implemented by the supplier. Environmental sustainability selection criteria are about the environmental performance and practices that the supplier is aware of to protect the environment (Zimmer et al., 2015). Supplier assessments began to consider all three pillars of sustainability in the decision-making process. The criteria for selecting the best supplier were identified by the experts based on the Triple Bottom Line (TBL) framework, incorporating social, environmental, and economic dimensions into the evaluation of sustainability (Zimmer et al., 2015). Many researchers identified the significance of the Quality (Q), Cost (C), and Delivery Time (DT) (Afrasiabi et al., 2022; Flores, 2021; Menon and Ravi, 2022; Althaqafi, 2023). Technology Capability (Govindan et al., 2012; Haseli et al., 2021; Flores, 2021) is a vital economic indicator in evaluating the suppliers in their study. Zimmer et al., (2015) reviewed publications between 1977 and 2014, focusing on sustainable supplier management, where around 60 papers developed a conceptual framework on environmental

supplier selection. Green Corporate Social Image (GCSI), (Ahmadi et al., (2016), is an approach towards the environmental sustainability of supplier selection based on the reputation they are ready to build in the corporate image and social agreement. Emroozi et al., (2023) suggest that Pollution Control (PC) is one of the most important criteria in environmental stability, where the air quality, water waste, and chemical emission of the supplier are considered. Environmental Management Initiatives (EMI) (Haseli et al., 2021; Flores, 2021; Menon and Ravi, 2022) are innovative initiatives of the supplier for the well-being of the stakeholder and the support activities that show the commitment towards the environment. Work Safety and Labour Health (WSLH) (Ahmadi et al., 2016; Govindan et al., 2012) considers safety management and stakeholders' rights in social factors. (Aslani et al., 2020; Govindan et al., 2012) studies demonstrated the importance of the welfare of the local community through healthcare, community projects, and economic welfare that could uplift the stakeholders of the community through the criteria Local Community Influence (LCI). Table 1 contains the sustainable supplier criteria. In this study, Fig. 2. The framework identifies the most suitable sustainable supplier criteria identified by the experts.

GRA

In 1982, Deng proposed the grey system theory; the essential content of grey set theory is grey generating space, grey forecasting, grey decision making, and so on (Deng, 1989) In grey relational analysis, grey generally represents the unknown information, where black represents that not all the information is available, and white is when there is all the needed information is available. Missed or fuzzy, poor, or incomplete information is

Table 2: Basic operations

S No	Basic Operation		Equation
1	Addition	$\otimes Gr_1 + \otimes Gr_2 = [\underline{Gr_1 + Gr_2}, \overline{Gr_1 + Gr_2}]$	(5)
2	Subtraction	$\otimes Gr_1 - \otimes Gr_2 = [\underline{Gr_1 - Gr_2}, \overline{Gr_1 - Gr_2}]$	(6)
3	Multiplication	$\otimes Gr_1 \times \otimes Gr_2 = [\min(\underline{Gr_1 Gr_2}, \underline{Gr_1} \overline{Gr_2}, \overline{Gr_1} \underline{Gr_2}, \overline{Gr_1 Gr_2}), \max(\overline{Gr_1 Gr_2}, \overline{Gr_1} \overline{Gr_2}, \underline{Gr_1} \underline{Gr_2}, \underline{Gr_1 Gr_2})]$	(7)
4	Division	$\otimes Gr_1 \div \otimes Gr_2 = [\underline{Gr_1}, \overline{Gr_1}] \times [\frac{1}{\underline{Gr_2}}, \frac{1}{\overline{Gr_2}}]$	(8)

Table 3 Scenarios on their relationships

S No	Scenario	Meaning	Denoted as	Possibility Degree
1	$\underline{Gr_1} = \underline{Gr_2}$ and $\overline{Gr_1} = \overline{Gr_2}$	$\otimes Gr_1$ is absolutely equal to $\otimes Gr_2$	$\otimes Gr_1 \cong \otimes Gr_2$	$P\{\otimes Gr_1 \leq \otimes Gr_2\} = 0.5$
2	$\underline{Gr_2} > \underline{Gr_1}$	$\otimes Gr_2$ is larger than $\otimes Gr_1$	$\otimes Gr_2 > \otimes Gr_1$	$P\{\otimes Gr_1 \leq \otimes Gr_2\} = 1$
3	$\underline{Gr_2} < \underline{Gr_1}$	$\otimes Gr_2$ is smaller than $\otimes Gr_1$	$\otimes Gr_2 < \otimes Gr_1$	$P\{\otimes Gr_1 \leq \otimes Gr_2\} = 0$
4	If grey numbers have an overlapping intervals	$\otimes Gr_2$ is larger than $\otimes Gr_1$ $\otimes Gr_2$ is smaller than $\otimes Gr_1$	$\otimes Gr_2 > \otimes Gr_1$ $\otimes Gr_2 < \otimes Gr_1$	$P\{\otimes Gr_1 \leq \otimes Gr_2\} > 0.5$ $P\{\otimes Gr_1 \leq \otimes Gr_2\} < 0.5$

called the grey system (Chakraborty et al., 2023). It measures the relational degree of the factors. In GRA, the grey relational grade (GRG) is represented as the correlation between a set of experimental results and the ideal value for multiple performance characteristics. The higher the GRG, the stronger the correlation (Chakraborty et al., 2023). Multi-attribute decision making is converted into a single-attribute decision-making problem, so the comparison of the attributes is turned into a single value. In Table 4. The GRA method is used in various sectors like facility layout problems, dispatching rule selection problems, and time series data (Kuo et al., 2008). Grey theory considers the condition of vagueness and fuzziness. (G. Li et al., 2007).

Definition 1: Grey theory is applied when information is known, and some information is unknown. The unknown information is described in terms of grey numbers. A grey number operation is defined on sets of intervals instead of individual real numbers.

Definition 2: The grey number is a number having uncertain information. The numbers are represented in the interval [a,b] where 'a' is the lower limit and 'b' is the upper limit. The interval represents the possible range of values for the uncertain data. A degree of uncertainty is associated with linguistic ratings, and

they can be converted into interval values, such as grey numbers. It is generally represented as

$$\otimes G, \text{ where } \otimes G = G \left[\frac{\mu}{\underline{\mu}} \right] \quad (1)$$

Definition 3: The definition of the lower limit grey number is

$$\otimes G_l = [\underline{G}, \infty) \quad (2)$$

Definition 4: The upper limit grey number is described as

$$\otimes G_u = (-\infty, \overline{G}] \quad (3)$$

Definition 5: With estimations of the lower limit of G and upper limit of G available, a grey number can be represented as a grey number interval as

$$\otimes G = [\underline{G}, \overline{G}] \quad (4)$$

Definition 6: The grey number operations, such as addition, subtraction, multiplication, and division, are performed on the interval-valued grey numbers. G. Li et al., (2006) defined the operations on grey numbers where $\otimes Gr_1 = [\underline{Gr_1}, \overline{Gr_1}]$ and $\otimes Gr_2 = [\underline{Gr_2}, \overline{Gr_2}]$ are grey numbers, and the basic operations are shown in

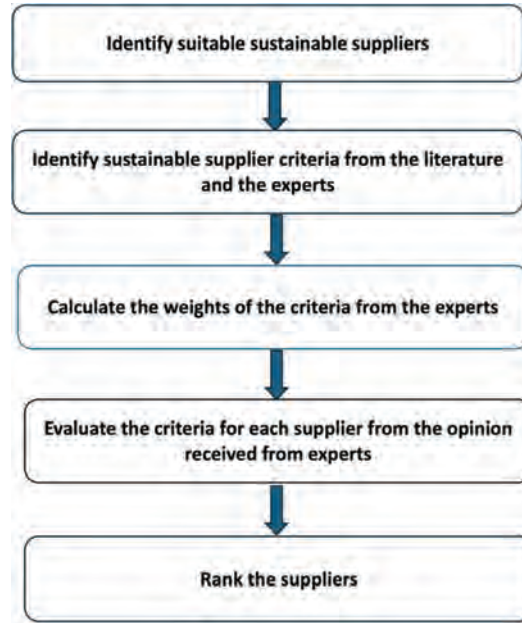


Fig. 1: Sustainable Supplier Framework

Table 2.

Definition 7: The length of grey number $\otimes G$ is

$$L(\otimes G) = \bar{G} - \underline{G} \quad (9)$$

Definition 8: The possibility degree between two grey numbers

$$\begin{aligned} \otimes Gr_1 &= [\underline{Gr}_1, \bar{Gr}_1] \text{ and } \otimes Gr_2 = [\underline{Gr}_2, \bar{Gr}_2] \\ P\{\otimes Gr_1 \leq \otimes Gr_2\} &= \frac{\max(0, L^* - \max(0, \bar{Gr}_1 - \underline{Gr}_2))}{L^*} \quad (10) \end{aligned}$$

where $L^* = L(\otimes Gr_1) + L(\otimes Gr_2)$.

Based on the position of grey number intervals $\otimes Gr_1$, $\otimes Gr_2$, there could be four different scenarios in the relationship between them, which are described in Table 3.

Proposed methodology

Modified GRA

The objective of modified grey relational analysis is to simply the computation and order the preference of the best supplier by using relative closeness to the positive ideal and negative ideal suppliers. The RC_i^* denotes the relative closeness

to the positive ideal solution, indicating a greater distance from the minimum ideal possibility degree (0.5), and to the negative ideal solution, indicating a closer proximity to the maximum possibility degree (0.5). The grey possibility degree between each of the suppliers against the ideal supplier and the negative ideal supplier is computed. A positive ideal solution is considered the best performance value, and the negative ideal solution is considered the worst performance value.

GRA is robust to data variability and less sensitive to outliers, ensuring reliability in real-world applications. It captures subjective judgments; the research aims to prioritise suppliers based on both quantitative and qualitative factors. This combination enhances the decision-making process by providing a systematic approach to ranking alternatives and identifying the most promising supplier.

In this research, to select the best supplier, a modified grey relational analysis is proposed. Let $SS = \{SS_1, SS_2, \dots, SS_m\}$ be a collection of m potential suppliers, and let $C = \{C_1, C_2, \dots, C_n\}$ be a collection of n supplier evaluation factors. The decision makers provide ratings on the linguistic scale to the evaluation criteria and the supplier. Also, the decision makers rate each of the suppliers for each of the criteria on a

Table 4: The scale of supplier selection evaluation criteria weights $\otimes w$ (G. Li et al., 2006)

Linguistic Scale	$\otimes w$ (Grey Number Scale)
Very low (VL)	[0.0, 0.1]
Low (VL)	[0.1, 0.3]
Medium low (ML)	[0.3, 0.4]
Medium (M)	[0.4, 0.5]
Medium high (MH)	[0.5, 0.6]
High (H)	[0.6, 0.9]
Very high (VH)	[0.9, 1.0]

Table 5: Supplier evaluation criteria rating scale

Linguistic Scale	$\otimes G$ (Grey Number)
Very poor (VP)	[0, 1]
Poor (P)	[1, 3]
Medium poor (MP)	[3, 4]
Fair (F)	[4, 5]
Medium good (MG)	[5, 6]
Good (G)	[6, 9]
Very good (VG)	[9, 10]

linguistic scale. The linguistic scale is converted into a grey number scale in Table 4.

The decision makers provide linguistic scale values for the criteria weights. The supplier selection evaluation criteria ratings in a linguistic scale can be converted into a grey numbers scale, given in Table 5.

The Modified Grey-based Multi-Criteria Decision-Making method involves the following ten steps.

Step 1: The criteria weight of the criteria C_j , assuming a group of K decision makers, can be calculated as follows:

$$\otimes C_j = \frac{1}{K} [\otimes C_j^1 + \otimes C_j^2 + \dots + \otimes C_j^K] \quad (11)$$

Where $\otimes C_j^k$ ($j=1,2,\dots,n$) is the k th decision maker's criterion weight, which is represented by the grey number $\otimes C_j^k = [\underline{C}_j^k, \overline{C}_j^k]$.

Step 2: Decision makers provide linguistic ratings to each of the criteria, for each of the supplier ratings is converted into the grey scale as given in Table 7.

The grey scale rating of the i th supplier alternative for the j th criterion is given by:

$$\otimes G_{ij} = \frac{1}{K} [\otimes G_{ij}^1 + \otimes G_{ij}^2 + \dots + \otimes G_{ij}^K] \quad (12)$$

where $\otimes G_{ij}^K$ ($i=1,2,\dots,m$; $j=1,2,\dots,n$) is the criterion rating value of the K th decision maker.

It is represented by the grey number as $\otimes G_{ij}^K = [\underline{G}_{ij}^K, \overline{G}_{ij}^K]$.

Step 3: Develop the grey decision matrix

$$D = \begin{bmatrix} \otimes G_{11} & \dots & \otimes G_{1n} \\ \vdots & \ddots & \vdots \\ \otimes G_{m1} & \dots & \otimes G_{mn} \end{bmatrix} \quad (13)$$

where $\otimes G_{ij}$ provides the grey scale rating of the i th supplier alternative for the j th criterion.

Step 4: Normalisation of the grey decision matrix

$$D^* = \begin{bmatrix} \otimes G_{11}^* & \dots & \otimes G_{1n}^* \\ \vdots & \ddots & \vdots \\ \otimes G_{m1}^* & \dots & \otimes G_{mn}^* \end{bmatrix} \quad (14)$$

where for a benefit attribute $\otimes G_{ij}^* = \left[\frac{G_{ij}}{G_j^{\max}}, \frac{\overline{G}_{ij}}{G_j^{\max}} \right]$ with $G_j^{\max} = \max_{1 \leq i \leq m} \{G_{ij}\}$;

for a cost attribute $\otimes G_{ij}^* = \left[\frac{G_j^{\min}}{G_{ij}}, \frac{G_j^{\min}}{\overline{G}_{ij}} \right]$ with $G_j^{\min} = \min_{1 \leq i \leq m} \{G_{ij}\}$;

Step 5: This step involves computing the weighted normalisation table considering the criteria weights.

$$D_w^* = \begin{bmatrix} \otimes V_{11}^* & \dots & \otimes V_{1n}^* \\ \vdots & \ddots & \vdots \\ \otimes V_{m1}^* & \dots & \otimes V_{mn}^* \end{bmatrix} \quad (15)$$

where $\otimes V_{ij}^* = \otimes G_{ij}^* \times \otimes C_j$

Step 6: For m possible supplier alternatives $SS=$

$\{SS_1, SS_2, \dots, SS_m\}$, the ideal supplier alternative is defined as $SS_{\max} = \{G_1^{\max}, G_2^{\max}, \dots, G_n^{\max}\}$ where $SS_{\max}$ is computed as

$$\left\{ \left[\max_{1 \leq i \leq m} V_{i1}, \max_{1 \leq i \leq m} \overline{V}_{i1} \right], \left[\max_{1 \leq i \leq m} V_{i2}, \max_{1 \leq i \leq m} \overline{V}_{i2} \right], \dots, \left[\max_{1 \leq i \leq m} V_{in}, \max_{1 \leq i \leq m} \overline{V}_{in} \right] \right\} \quad (16)$$

Step 7: Compute the grey possibility degree between the compared supplier alternatives set

$SS_{\max} = \{SS_1, SS_2, \dots, SS_m\}$ and ideal supplier alternative $SS_{\max}$.

$$L_i^+ = P\{SS_i \leq SS_{\max}\} = \frac{1}{n} \sum_{j=1}^n P\{\otimes V_{ij} \leq \otimes G_j^{\max}\} \quad (17)$$

Step 8: Compute the grey possibility degree between the negative ideal supplier $SS_{\min}$ and the supplier alternatives. It is defined as

$$L_i^- = P\{SS_{\min} \leq SS_i\} = \frac{1}{n} \sum_{j=1}^n P\{\otimes G_j^{\min} \leq \otimes V_{ij}\} \quad (18)$$

Step 9: Calculate the relative closeness index, which provides the closeness of the supplier to the ideal supplier using the following equation

$$RC_i^* = \frac{L_i^-}{L_i^- + (1 - L_i^+)} \quad (19)$$

Step 10: Rank the supplier in descending order of the relative closeness index. The higher the RC_i^* for a particular supplier better the ranking of the supplier. The supplier with the highest relative closeness index is selected as the supplier.

RESULT AND DISCUSSION

Following the initial screening, ten suppliers were shortlisted for further evaluation based on criteria defined by industry experts. A panel of four supply chain experts assessed the potential suppliers and the key criteria for selecting the most suitable one. These experts, each possessing substantial experience in supply chain management, were instrumental in identifying industry-relevant evaluation parameters.

Expert 1, with 15 years of experience, serves as the Divisional Manager in the Supplier Management Division.

Expert 2 has 12 years of experience and currently holds the position of Manager in the Part Control Division.

Expert 3, with 18 years of expertise in the Supplier Quality Division, is designated as Deputy General Manager.

Expert 4, with 16 years of experience, manages the Scheduling and Procurement Division. To mitigate ambiguity in the evaluation process, the experts employed linguistic terms for assessing supplier performance.

Application of grey-based methodology

Step 1: The criteria weights were evaluated from 4 experts, and the criteria weights were linguistic variables in GRA. Table 6. provides the linguistic value of the experts. Each decision maker k assigns a grey weight to each criterion C_j . The overall weight for each criterion C_j is obtained by averaging across all K decision makers, which yields a combined grey weight for each criterion.

Step 2: The rating of each supplier for the selected criteria is calculated from 4 experts using linguistic variables. The given ratings are converted into grey numbers. Table 7. Provides the value of the supplier

Table 6: Criteria Weights of the decision maker

Criteria	Exprt 1	Exprt 2	Exprt 3	Exprt 4	Criteria Weights	
Q	H	VH	VH	MH	0.725	0.875
C	MH	H	MH	M	0.500	0.650
DT	M	H	H	H	0.550	0.800
TC	VH	H	VH	H	0.750	0.950
GCSI	M	MH	H	MH	0.450	0.650
PC	ML	M	MH	H	0.450	0.600
EMI	M	MH	H	MH	0.500	0.650
WSLH	H	VH	VH	H	0.750	0.950
LCI	ML	M	MH	M	0.400	0.500

Table 7: Supplier ratings by the experts

Criteria	Suppliers	Exprt 1	Exprt 2	Exprt 3	Exprt 4	Grey Ratings	
Q	SI1	G	MG	VG	F	6.0	7.5
	SI2	MG	G	F	MP	4.5	6.0
	SI3	VG	VG	G	MG	7.3	8.8
	SI4	MP	P	F	MG	3.3	4.5
	SI5	G	G	MG	G	5.8	8.3
	SI6	F	MG	G	VG	6.0	7.5
	SI7	VG	G	G	MG	6.5	8.5
	SI8	P	MP	F	G	3.5	5.3
	SI9	MG	VG	G	F	7.3	7.5
	SI10	G	F	MG	VG	6.0	7.5
C	SI1	F	MG	G	VG	6.0	7.5
	SI2	VG	G	MG	F	6.0	7.5
	SI3	G	MG	VG	P	5.3	7.0
	SI4	MP	F	P	G	3.5	5.3
	SI5	G	VG	G	MG	6.5	8.5
	SI6	P	MP	F	MG	3.3	4.5
	SI7	VG	G	MG	G	6.5	8.5
	SI8	MP	P	F	VG	4.3	5.5
	SI9	G	MG	VG	P	5.3	7.0
	SI10	MG	G	F	VG	6.0	7.5
DT	SI1	MG	G	VG	P	5.3	7.0
	SI2	F	MP	G	MG	4.5	6.0
	SI3	VG	G	MG	F	6.0	7.5
	SI4	P	F	MP	G	3.5	5.3
	SI5	G	MG	VG	MP	5.8	7.3
	SI6	VG	G	F	MG	6.0	7.5
	SI7	MP	F	G	VG	5.5	7.0
	SI8	P	MG	G	G	4.5	6.8
	SI9	VG	G	MG	F	6.0	7.5
	SI10	G	VG	MG	F	6.0	7.5
TC	SI1	VG	G	MG	F	6.0	7.5
	SI2	F	MP	G	VG	5.5	7.0
	SI3	G	MG	VG	P	5.3	7.0
	SI4	MP	F	P	G	3.5	5.3
	SI5	G	VG	G	MG	6.5	8.5
	SI6	P	MP	F	MG	3.3	4.5
	SI7	VG	G	MG	G	6.5	8.5
	SI8	MP	P	F	VG	4.3	5.5
	SI9	G	MG	VG	P	5.3	7.0
	SI10	MG	G	F	VG	6.0	7.5
GCSI	SI1	P	G	F	MP	3.5	5.3
	SI2	G	F	G	G	5.0	7.0
	SI3	VG	G	G	F	6.3	8.3
	SI4	MP	P	F	G	3.5	5.3
	SI5	F	F	G	VG	5.8	7.3
	SI6	G	G	G	MP	5.3	7.8
	SI7	G	MP	MP	G	4.5	6.5
	SI8	P	F	F	G	3.8	5.5
	SI9	P	G	F	MP	3.5	5.3
	SI10	VG	G	MG	G	6.5	8.5
PC	SI1	G	G	F	MP	4.8	6.8
	SI2	VG	MG	G	F	6.0	7.5
	SI3	P	P	F	G	3.0	5.0
	SI4	G	MG	F	G	5.3	7.3
	SI5	MP	G	G	F	4.8	6.8
	SI6	VG	G	F	MG	6.0	7.5
	SI7	G	G	P	F	4.3	6.5
	SI8	F	G	MG	MG	5.0	6.5
	SI9	VG	G	MG	F	6.0	7.5
	SI10	MP	F	G	VG	5.5	7.0
EMI	SI1	G	F	G	G	5.5	8.0
	SI2	MP	MG	MP	F	3.8	4.8
	SI3	MG	G	VG	F	6.0	7.5

Table 7: Supplier ratings by the experts

Criteria	Suppliers	Exprt 1	Exprt 2	Exprt 3	Exprt 4	Grey Ratings	
WSLH	SI4	G	F	P	F	3.8	5.5
	SI5	G	F	G	G	5.5	8.0
	SI6	MG	VG	VG	G	7.3	8.8
	SI7	G	MP	MP	G	4.5	6.5
	SI8	VG	G	G	G	6.8	9.3
	SI9	G	F	F	MG	4.8	6.3
	SI10	MG	G	G	VG	6.5	8.5
	SI1	MP	P	F	MP	2.8	4.0
	SI2	F	F	MG	G	4.8	6.3
	SI3	G	G	VG	F	6.3	8.3
LCI	SI4	G	MP	G	G	5.3	7.8
	SI5	P	F	VG	F	4.5	5.8
	SI6	P	G	P	G	3.5	6.0
	SI7	MG	G	G	MG	5.5	7.5
	SI8	VG	G	MP	F	5.5	7.0
	SI9	F	G	VG	G	6.3	8.3
	SI10	MG	G	G	G	5.8	8.3
	SI1	G	G	MG	F	5.3	7.3
	SI2	P	F	G	VG	5.0	6.8
	SI3	F	MG	G	G	5.3	7.3
	SI4	G	F	G	MG	5.3	7.3
	SI5	G	G	VG	F	6.5	8.3
	SI6	MG	VG	MP	F	5.3	6.3
	SI7	MP	G	G	VG	6.0	8.0
	SI8	G	MP	G	MP	4.5	6.5
	SI9	F	G	VG	G	6.3	8.3
	SI10	G	F	G	F	5.0	7.0

Table 8: Grey decision matrix

Criteria/ Supplier	SI1	SI2	SI3	SI4	SI5	SI6	SI7	SI8	SI9	SI10
Q	6.0	4.5	7.3	3.3	5.8	6.0	6.5	3.5	7.3	6.0
	7.5	6.0	8.8	4.5	8.3	7.5	8.5	5.3	7.5	7.5
C	6.0	6.0	5.3	3.5	6.5	3.3	6.5	4.3	5.3	6.0
	7.5	7.5	7.0	5.3	8.5	4.5	8.5	5.5	7.0	7.5
DT	5.3	4.5	6.0	3.5	5.8	6.0	5.5	4.5	6.0	6.0
	7.0	6.0	7.5	5.3	7.3	7.5	7.0	6.8	7.5	7.5
TC	6.0	5.5	5.3	3.5	6.5	3.3	6.5	4.3	5.3	6.0
	7.5	7.0	7.0	5.3	8.5	4.5	8.5	5.5	7.0	7.5
GCSI	3.5	5.0	6.3	3.5	5.8	5.3	4.5	3.8	3.5	6.5
	5.3	7.0	8.3	5.3	7.3	7.8	6.5	5.5	5.3	8.5
PC	4.8	6.0	3.0	5.3	4.8	6.0	4.3	5.0	6.0	5.5
	6.8	7.5	5.0	7.3	6.8	7.5	6.5	6.5	7.5	7.0
EMI	5.5	3.8	6.0	3.8	5.5	7.3	4.5	6.8	4.8	6.5
	8.0	4.8	7.5	5.5	8.0	8.8	6.5	9.3	6.3	8.5
WSLH	2.8	4.8	6.3	5.3	4.5	3.5	5.5	5.5	6.3	5.8
	4.0	6.3	8.3	7.8	5.8	6.0	7.5	7.0	8.3	8.3
LCI	5.3	5.0	5.3	5.3	6.5	5.3	6.0	4.5	6.3	5.0
	7.3	6.8	7.3	7.3	8.3	6.3	8.0	6.5	8.3	7.0

rating. The ratings from all the decision makers are averaged to get a combined rating.

Step 3: Develop the grey decision matrix, which is shown in Table 8. A grey decision matrix D is formed, where each element is the grey rating $\otimes G_{ij}$, supplier i for criterion j .

Step 4: Normalization of the grey decision matrix is provided in Tables 9 and 10. Normalization ensures comparability across criteria by transforming the ratings into a $[0,1]$ range. This yields a normalized grey decision matrix D^*

Step 5: A Grey weighted normalization matrix is

Table 10: Normalized grey decision matrix

Criteria/ Supplier	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
(Q)	0.5417	0.7222	0.4483	1.0000	0.5652	0.5417	0.5000	0.9286	0.4483	0.5417
	0.4333	0.5417	0.3714	0.7222	0.3939	0.4333	0.3824	0.6190	0.4333	0.4333
(C)	0.5417	0.5417	0.6190	0.9286	0.5000	1.0000	0.5000	0.7647	0.6190	0.5417
	0.4333	0.4333	0.4643	0.6190	0.3824	0.7222	0.3824	0.5909	0.4643	0.4333
(DT)	0.6667	0.7778	0.5833	1.0000	0.6087	0.5833	0.6364	0.7778	0.5833	0.5833
	0.5000	0.5833	0.4667	0.6667	0.4828	0.4667	0.5000	0.5185	0.4667	0.4667
(TC)	0.5417	0.5909	0.6190	0.9286	0.5000	1.0000	0.5000	0.7647	0.6190	0.5417
	0.4333	0.4643	0.4643	0.6190	0.3824	0.7222	0.3824	0.5909	0.4643	0.4333
(GCSI)	1.0000	0.7000	0.5600	1.0000	0.6087	0.6667	0.7778	0.9333	1.0000	0.5385
	0.6667	0.5000	0.4242	0.6667	0.4828	0.4516	0.5385	0.6364	0.6667	0.4118
(PC)	0.6316	0.5000	1.0000	0.5714	0.6316	0.5000	0.7059	0.6000	0.5000	0.5455
	0.4444	0.4000	0.6000	0.4138	0.4444	0.4000	0.4615	0.4615	0.4000	0.4286
(EMI)	0.6818	1.0000	0.6250	1.0000	0.6818	0.5172	0.8333	0.5556	0.7895	0.5769
	0.4688	0.7895	0.5000	0.6818	0.4688	0.4286	0.5769	0.4054	0.6000	0.4412
(WSLH)	1.0000	0.5789	0.4400	0.5238	0.6111	0.7857	0.5000	0.5000	0.4400	0.4783
	0.6875	0.4400	0.3333	0.3548	0.4783	0.4583	0.3667	0.3929	0.3333	0.3333
(LCI)	0.8571	0.9000	0.8571	0.8571	0.6923	0.8571	0.7500	1.0000	0.7200	0.9000
	0.6207	0.6667	0.6207	0.6207	0.5455	0.7200	0.5625	0.6923	0.5455	0.6429

Table 11: Normalized grey decision matrix

Criteria/ Supplier	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
(Q)	0.6857	0.5143	0.8286	0.3714	0.6571	0.6857	0.7429	0.4000	0.8286	0.6857
	0.8571	0.6857	1.0000	0.5143	0.9429	0.8571	0.9714	0.6000	0.8571	0.8571
(C)	0.7059	0.7059	0.6176	0.4118	0.7647	0.3824	0.7647	0.5000	0.6176	0.7059
	0.8824	0.8824	0.8235	0.6176	1.0000	0.5294	1.0000	0.6471	0.8235	0.8824
(DT)	0.7000	0.6000	0.8000	0.4667	0.7667	0.8000	0.7333	0.6000	0.8000	0.8000
	0.9333	0.8000	1.0000	0.7000	0.9667	1.0000	0.9333	0.9000	1.0000	1.0000
(TC)	0.7059	0.6471	0.6176	0.4118	0.7647	0.3824	0.7647	0.5000	0.6176	0.7059
	0.8824	0.8235	0.8235	0.6176	1.0000	0.5294	1.0000	0.6471	0.8235	0.8824
(GCSI)	0.4118	0.5882	0.7353	0.4118	0.6765	0.6176	0.5294	0.4412	0.4118	0.7647
	0.6176	0.8235	0.9706	0.6176	0.8529	0.9118	0.7647	0.6471	0.6176	1.0000
(PC)	0.6333	0.8000	0.4000	0.7000	0.6333	0.8000	0.5667	0.6667	0.8000	0.7333
	0.9000	1.0000	0.6667	0.9667	0.9000	1.0000	0.8667	0.8667	1.0000	0.9333
(EMI)	0.5946	0.4054	0.6486	0.4054	0.5946	0.7838	0.4865	0.7297	0.5135	0.7027
	0.8649	0.5135	0.8108	0.5946	0.8649	0.9459	0.7027	1.0000	0.6757	0.9189
(WSLH)	0.3333	0.5758	0.7576	0.6364	0.5455	0.4242	0.6667	0.6667	0.7576	0.6970
	0.4848	0.7576	1.0000	0.9394	0.6970	0.7273	0.9091	0.8485	1.0000	1.0000
(LCI)	0.6364	0.6061	0.6364	0.6364	0.7879	0.6364	0.7273	0.5455	0.7576	0.6061
	0.8788	0.8182	0.8788	0.8788	1.0000	0.7576	0.9697	0.7879	1.0000	0.8485

computed as in Eq.15 and is listed below in Tables 11 and 12. Each normalized grey value is multiplied by its criterion weight to reflect importance. This results in a weighted normalized matrix that integrates both ratings and criteria weights.

Step 6: The ideal supplier is one of the best performers in all criteria. SS_{max} is computed.

$SS_{max} = \{[0.600, 0.875], [0.382, 0.650], [0.440, 0.800], [0.573, 0.950], [0.344, 0.655], [0.360, 0.600],$

$[0.391, 0.650], [0.568, 0.950], [0.315, 0.500]\}$

Step 7: The grey possibility degree between the supplier alternatives SS_i ($i=1,2,3,...10$). This step calculates how close each supplier SS_i is to the ideal supplier. According to Eq. 17, the values are listed below in Table 13. The function P represents the possibility degree measuring the overlap or closeness between intervals

Step 8: The grey possibility degree between

Table 11: Grey weighted normalization table

Criteria/ Supplier	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
(Q)	0.3927	0.5236	0.3250	0.7250	0.4098	0.3927	0.3625	0.6732	0.3250	0.3927
	0.3792	0.4740	0.3250	0.6319	0.3447	0.3792	0.3346	0.5417	0.3792	0.3792
(C)	0.2708	0.2708	0.3095	0.4643	0.2500	0.5000	0.2500	0.3824	0.3095	0.2708
	0.2817	0.2817	0.3018	0.4024	0.2485	0.4694	0.2485	0.3841	0.3018	0.2817
(DT)	0.3667	0.4278	0.3208	0.5500	0.3348	0.3208	0.3500	0.4278	0.3208	0.3208
	0.4000	0.4667	0.3733	0.5333	0.3862	0.3733	0.4000	0.4148	0.3733	0.3733
(TC)	0.4063	0.4432	0.4643	0.6964	0.3750	0.7500	0.3750	0.5735	0.4643	0.4063
	0.4117	0.4411	0.4411	0.5881	0.3632	0.6861	0.3632	0.5614	0.4411	0.4117
(GCSI)	0.4500	0.3150	0.2520	0.4500	0.2739	0.3000	0.3500	0.4200	0.4500	0.2423
	0.4333	0.3250	0.2758	0.4333	0.3138	0.2935	0.3500	0.4136	0.4333	0.2676
(PC)	0.2842	0.2250	0.4500	0.2571	0.2842	0.2250	0.3176	0.2700	0.2250	0.2455
	0.2667	0.2400	0.3600	0.2483	0.2667	0.2400	0.2769	0.2769	0.2400	0.2571
(EMI)	0.3409	0.5000	0.3125	0.5000	0.3409	0.2586	0.4167	0.2778	0.3947	0.2885
	0.3047	0.5132	0.3250	0.4432	0.3047	0.2786	0.3750	0.2635	0.3900	0.2868
(WSLH)	0.7500	0.4342	0.3300	0.3929	0.4583	0.5893	0.3750	0.3750	0.3300	0.3587
	0.6531	0.4180	0.3167	0.3371	0.4543	0.4354	0.3483	0.3732	0.3167	0.3167
(LCI)	0.3429	0.3600	0.3429	0.3429	0.2769	0.3429	0.3000	0.4000	0.2880	0.3600
	0.3103	0.3333	0.3103	0.3103	0.2727	0.3600	0.2813	0.3462	0.2727	0.3214

Table 12: Grey weighted normalization table

Criteria/ Supplier	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
(Q)	0.4740	0.6319	0.3922	0.8750	0.4946	0.4740	0.4375	0.8125	0.3922	0.4740
	0.3142	0.3927	0.2693	0.5236	0.2856	0.3142	0.2772	0.4488	0.3142	0.3142
(C)	0.3521	0.3521	0.4024	0.6036	0.3250	0.6500	0.3250	0.4971	0.4024	0.3521
	0.2167	0.2167	0.2321	0.3095	0.1912	0.3611	0.1912	0.2955	0.2321	0.2167
(DT)	0.5333	0.6222	0.4667	0.8000	0.4870	0.4667	0.5091	0.6222	0.4667	0.4667
	0.2750	0.3208	0.2567	0.3667	0.2655	0.2567	0.2750	0.2852	0.2567	0.2567
(TC)	0.5146	0.5614	0.5881	0.8821	0.4750	0.9500	0.4750	0.7265	0.5881	0.5146
	0.3250	0.3482	0.3482	0.4643	0.2868	0.5417	0.2868	0.4432	0.3482	0.3250
(GCSI)	0.6500	0.4550	0.3640	0.6500	0.3957	0.4333	0.5056	0.6067	0.6500	0.3500
	0.3000	0.2250	0.1909	0.3000	0.2172	0.2032	0.2423	0.2864	0.3000	0.1853
(PC)	0.3789	0.3000	0.6000	0.3429	0.3789	0.3000	0.4235	0.3600	0.3000	0.3273
	0.2000	0.1800	0.2700	0.1862	0.2000	0.1800	0.2077	0.2077	0.1800	0.1929
(EMI)	0.4432	0.6500	0.4063	0.6500	0.4432	0.3362	0.5417	0.3611	0.5132	0.3750
	0.2344	0.3947	0.2500	0.3409	0.2344	0.2143	0.2885	0.2027	0.3000	0.2206
(WSLH)	0.9500	0.5500	0.4180	0.4976	0.5806	0.7464	0.4750	0.4750	0.4180	0.4543
	0.5156	0.3300	0.2500	0.2661	0.3587	0.3438	0.2750	0.2946	0.2500	0.2500
(LCI)	0.4286	0.4500	0.4286	0.4286	0.3462	0.4286	0.3750	0.5000	0.3600	0.4500
	0.2483	0.2667	0.2483	0.2483	0.2182	0.2880	0.2250	0.2769	0.2182	0.2571

the negative ideal supplier $SS_{\min}$ and the supplier alternative SS_i $\{i=1,2,3,...,10\}$. According to Eq. 18, the values are listed below in Table 14. The negative ideal supplier $SS_{\min}$ has the worst performance across criteria. This step calculates how far a supplier is from this negative ideal.

Step 9: According to Eq. 19 relative closeness index is computed, and the values are listed below in Table 15. The closeness index reflects how close

a supplier is to the ideal and how far from the anti-ideal. A higher RC_i^* means the supplier is closer to the ideal solution.

Step 10: Sorting the relative closeness index in descending order. The RC_i^* represents the distance to the positive ideal solution (L_i^+), where it is farther from the minimum ideal possibility degree 0.5 and the negative ideal solution (L_i^-) where it is closer to a maximum of 0.5. The supplier with the highest

Table 13: Grey Possibility degree of layout alternatives with ideal supplier

L_1^+	$P(SS_1 \leq SS_{\max})$	0.6499
L_2^+	$P(SS_2 \leq SS_{\max})$	0.6674
L_3^+	$P(SS_3 \leq SS_{\max})$	0.5749
L_4^+	$P(SS_4 \leq SS_{\max})$	0.7711
L_5^+	$P(SS_5 \leq SS_{\max})$	0.5371
L_6^+	$P(SS_6 \leq SS_{\max})$	0.6539
L_7^+	$P(SS_7 \leq SS_{\max})$	0.5377
L_8^+	$P(SS_8 \leq SS_{\max})$	0.6859
L_9^+	$P(SS_9 \leq SS_{\max})$	0.5897
L_{10}^+	$P(SS_{10} \leq SS_{\max})$	0.5374

Table 14: Grey Possibility degree of the negative ideal supplier with the supplier alternative

L_1^-	$P(SS_{\min} \leq SS_1)$	0.6517
L_2^-	$P(SS_{\min} \leq SS_2)$	0.6682
L_3^-	$P(SS_{\min} \leq SS_3)$	0.5047
L_4^-	$P(SS_{\min} \leq SS_4)$	0.7336
L_5^-	$P(SS_{\min} \leq SS_5)$	0.5602
L_6^-	$P(SS_{\min} \leq SS_6)$	0.7253
L_7^-	$P(SS_{\min} \leq SS_7)$	0.5764
L_8^-	$P(SS_{\min} \leq SS_8)$	0.6779
L_9^-	$P(SS_{\min} \leq SS_9)$	0.5700
L_{10}^-	$P(SS_{\min} \leq SS_{10})$	0.5300

Table 15: Relative closeness index of the supplier's alternative

RC_1^*	0.6506
RC_2^*	0.6676
RC_3^*	0.5428
RC_4^*	0.7622
RC_5^*	0.5476
RC_6^*	0.6770
RC_7^*	0.5550
RC_8^*	0.6834
RC_9^*	0.5814
RC_{10}^*	0.5340

relative closeness index RC_i^* is selected as the best supplier, as it is nearer to 1. The findings indicate that all suppliers demonstrate satisfactory performance, with the maximum relative closeness value observed being 0.76, and the minimum relative closeness value observed is 0.53. This reflects a highly competitive environment among the evaluated suppliers. More comprehensive by comparing both proximity to the best and distance from the worst. Table 15. The ranking order of the suppliers is as follows. $S_4 > S_8 > S_6 > S_2 > S_1 > S_9 > S_7 > S_5 > S_3 > S_{10}$. Hence, the research concludes that the supplier has the best sustainability performance in all three economic, environmental, and social sustainability based on the experts' opinions. To check the robustness of the

model, a comparative analysis with another MCDM method, TOPSIS, is applied, and the ranking suggests that the first three suppliers are supplier 4, supplier 8, and supplier 6, and there was a variation in the other supplier ranking.

CONCLUSION

Sustainable supplier selection is a complex process. This method facilitates a thorough evaluation of suppliers, delivering meaningful insights for decision-makers in the automobile sector. This comprehensive evaluation framework reflects an integrated approach that balances conventional performance indicators with contemporary sustainability considerations in supplier selection. The objective of the modified

grey relational analysis is to simplify decision making and less time-consuming by converting the linguistic ratings into a grey number, and the method compares each supplier against an ideal supplier and a negative ideal supplier. The grey possibility degree between each of the suppliers against the ideal supplier and the negative ideal supplier is computed. The supplier with the highest relative closeness index is selected as the best supplier. This method is robust to data variability and less sensitive to outliers. It ultimately establishes a strong framework for selecting suppliers that adhere to sustainability principles while enhancing procurement efficiency. The selection alternative is based on the distance closest to the positive ideal supplier and farthest from the negative ideal supplier. Suppliers with an RC_i^* value below 0.5 should be excluded from consideration. One of the limitations of this study lies in the selection of evaluation criteria, which, although intended to provide a comprehensive assessment of supplier sustainability performance, may not fully encompass all relevant dimensions. Future research could expand the scope by incorporating additional criteria to enhance the robustness of supplier selection. As the identification of criteria represents the initial and crucial step in the evaluation process, it significantly influences the outcome. Furthermore, analysis of the responses indicated that the selected criteria were not uniformly influenced by the three pillars of sustainability—economic, environmental, and social—highlighting the need for a more balanced approach in future investigations. Future research may explore the integration of advanced multi-criteria decision-making (MCDM) techniques, such as Intuitionistic Fuzzy Sets, Fuzzy Rough Sets, and Interval-Valued Fuzzy Sets. These methodologies offer robust capabilities for handling uncertainty and can be effectively applied across diverse decision-making contexts. Evaluation can be made for a dynamic environment considering possible events. Potential applications include supplier selection in the manufacturing sector, project or portfolio selection in construction, equipment selection in warehouse operations, risk interaction assessment in green supply chain environments, evaluation of green port factors, and other strategic decisions within production and operations management. Furthermore, the proposed model can be enhanced by incorporating industry-specific evaluation criteria, enabling comparative analysis of outcomes across different domains.

AUTHOR CONTRIBUTIONS

Sai Keerthana.N carried out the idea development, methodology, software, review of literature, and manuscript preparation. Sudarsanam.S.K and Neelananarayanan.V corrected data, reviewed, and edited it, tested the software, and validated it.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the authors have witnessed ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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ABBREVIATIONS (NOMENCLATURE)

$\underline{G}, \bar{G}$	Lower and upper bounds of grey number
$\bar{\mu}$	Upper Limit
∞	Infinity
$\otimes$	Grey operator
$\otimes C_j^k (j=1, 2, \dots, n)$	K^{th} decision maker's criterion weight
$\otimes G_{ij}^K (i=1, 2, \dots, m; j=1, 2, \dots, n)$	criterion rating value of the K^{th} decision maker.
$\otimes V_{ij}^*$	Weighted and normalized grey value
$\otimes G$	Grey Number
ADGRA	Absolute Grey Relational Analysis
AHP	Analytical Hierarchy Process
ANP	Analytics Network Process
C	Cost
DEA	Data Envelopment Analysis
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DGRA	Dynamic Grey Relational Analysis
DT	Delivery Time
ELECTRE	Elimination and Choice Expressing Reality
EMI	Environmental Management Initiatives
EMS	Environmental Management System
Eq	Equation
ESE Sustainability	Economic, Social, Environmental sustainability
FAHP	Fuzzy Analytical Hierarchy Process
FBWM	Fuzzy Best Worst Method
FCP	Fuzzy Compromise Programming

GCSI	Green Corporate Social Image
GIFSS	Generalised Intuitionistic Fuzzy Soft Set
GRA	Grey Relational Analysis
HFLVIKOR	Hesitant Fuzzy Linguistic VIKOR
IFS	Intuitionistic Fuzzy Set
IFSS	Intuitionistic Fuzzy Soft Set
L^*	Length of grey number
LCI	Local Community Influence
MCDM	Multi-Criteria Decision Making
MOLP	Multi-Objective Linear Programming
MOORA	Multi-Objective Optimization based on Ratio Analysis
P	Possibility degree
PC	Pollution Control
Q	Quality
RC_i^*	Relative Closeness Index
SAW	Simple Additive Weighting
SSGRA	Second Synthetic Grey Relational Analysis
$SS^{\max}$	Positive ideal Supplier
$SS^{\min}$	Negative ideal supplier
TBL	Triple Bottom Line
TC	Technology Capabilities
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	ViseKriterijumska Optimizacija I Kompromisno Resenje
WSLH	Work Safety and Labour Health
μ	Lower Limit
—	

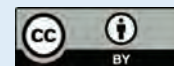
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REVIEW PAPER

Attenuating the volume of storm runoff flow through sustainable practices: A potential solution for flood-prone areas

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ABSTRACT

Floods in urban areas remain a critical threat to human life, health, and economic stability. This study focused on Nigeria's urban flooding, which has become a yearly occurrence. Recently, floods have been deepened by the climate change situation, urban planning lapses, and overwhelmed drainage infrastructures. Other factors intensifying urban flooding in Nigeria include rapid urbanization, choking off the natural spaces and vegetation with impervious surfaces, and accelerating stormwater runoff. The Nigerian government has implemented various flood risk management strategies, including the National Disaster Response Plan and flood control measures such as flood warning, preparedness, and responses. However, studies from the literature confirmed the insufficient understanding of flood events, such as the driving variables and uncertainties about watershed characteristics and climatic variability that impede flood risk management and prediction skills. Therefore, more proactive, sustainable strategies to handle floods are desperately needed in light of the numerous recent climate and flooding-related calamities ravaging the low-lying regions. Similarly, there is a paucity of empirical research on sustainable solutions for attenuating the volume of runoff that is seemingly resulting in flooding. This review fills this gap in the literature. More so, aligning with the United Nations' 2030 Agenda for Sustainable Development, the Sustainable Development Goals. Sustainable flood risk solutions touch on several SDGs, targeting all sustainable practices, resilient infrastructure, water management, sustainable cities and communities, and the sustainable use of terrestrial ecosystems. This review equally focuses on harnessing the potential embedded in the sustainable practices that can fit into other purposes.

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INTRODUCTION

Floods usually occur when a significant amount of water overflows into normally dry ground. This natural disaster is often triggered by extreme weather conditions such as heavy rainfall, resulting in accelerated storm runoff. Others include rising global temperatures, melting glaciers, and the thermal expansion of oceans, which all contribute to rising sea levels and subsequent flooding of coastal areas (Ujene *et al.*, 2020; Aderogba *et al.*, 2014; Ekpoh, 2015; Udoh, 2015). Evan, (2017) explained that flooding is one of the most frequent disasters, accounting for a significant proportion of natural disasters. It equally poses significant threats to plants, animals, humans, buildings, and infrastructure, with severe environmental impacts. The flooding menace has risen to become a global concern, generating hazards, disrupting lives, leading to property loss, and even causing ecosystem species as well as influencing the overall quality of the environment (Abubakar *et al.*, 2020). Due to its widespread and destructive nature, flooding has remained a critical factor used in assessing the environmental quality of residential neighborhoods, alongside other hazards like droughts, desertification, soil erosion, and tsunamis (Daniel & Udo, 2019). The potential consequence of flooding has been recognized as an annual destructive and damaging occurrence, prompting numerous international efforts to mitigate its impact (Bamidele *et al.*, 2019). The World Bank Group (2016) highlighted that flooding is among the most frequent and damaging natural disasters worldwide, severely impacting livelihoods. Bamidele *et al.*, (2019) pointed out that developing countries are particularly vulnerable due to inadequate environmental management and weak institutional frameworks that have resulted in unplanned building constructions in flood-prone areas and insufficient funding for the provision of essential infrastructure, like adequate drainage systems. (Komolafe, 2015; Nkwunonwo, 2016; Yesufu, 2016; Sule, 2016; Adetuji and Oleyele, 2018; Nwilo *et al.*, 2022). In developing countries, including Nigeria, floods are becoming a persistent environmental challenge, with studies indicating their frequent occurrence is associated with negative potential impact on livelihoods, social values, and economic activities (Abubakar *et al.*, 2020). Several scientists from literature have surveyed flood cases in different communities in Nigeria, evaluating their

impact on man's health, environment, and means of survival, indicating their intensity varies in severity with mitigation strategies (Umar and Gray, 2023). The reality is that all six geopolitical regions in Nigeria have been greatly affected by this flood menace. For instance, Onugba *et al.*, (2021) examined the impact of flooding on public health in flood-prone areas using basically the flood event of 2022 as a case study. Mitigation measures as suggested by the study include nature-based solutions such as retaining water with the use of natural elements in the form of wetlands, soil, marshes, and forests as a mechanism to capture water runoff for conservation. Ogunribido & Ogunribido, (2024) investigated the causes of the 2022 flood in 14 states in Nigeria, which affected all the geographical regions in Nigeria. The focus of the study was on environmental and socio-economic implications. Curbing measures focused on policy and strategies such as preparedness, flood forecasting, and accurate warning. Cirella and Iyalomhe (2018) assessed locations at risk of flood and prone to disaster, and suggested policy programmes to alleviate this hazard. Dalil *et al.*, (2015) evaluated the effect of flood calamities on human health in Ajegunle community, a highly crowded high residential zone in the Lagos state (South-west) region. Water-related diseases resulting from flooding were studied. Otomofa *et al.*, (2015) appraised the socio-economic impact of flooding affecting a community in Isoko South LGA of Delta state (South-south region). The activities mostly affected by flooding in the community include water quality, agricultural activities, education, and transportation. Obiwulu *et al.*, (2023) examined the impact of flooding on socioeconomic activities in the South-east region. The investigation revealed a huge potential impact of socioeconomic activities on the communities. Ezebube *et al.*, (2023) investigated contributory factors of continual flooding in the Onitsha (South-east) region. Flood events in this region have specifically resulted in land use and land cover changes and depletion with result showing an increase in built-up area, drastically reducing the natural vegetation, therefore, indicating more flooding cases. Chinwedu *et al.*, (2017) examined the effect of deteriorating climate conditions on the livelihoods of six villages along the Kaduna River basin (North-east) region. The study discovered that women were disproportionately affected due to their responsibility for running the home. The

situation of flood occurrences and frequency seems to be increasing despite all the efforts the Nigerian government has made. There is a need to consider other remedial options that have been successfully implemented in developed countries. Therefore, this study focused on lowering runoff volume through sustainable practices. The objectives anticipate aligning with the United Nations' 2030 Agenda for Sustainable Development SDGs, on sustainable flood risk solutions to ensure sustainable cities and communities

Prevalence of flood incidents in Nigeria

Flooding has remained a frequent natural disaster that occurs in Nigeria each year. The devastating effects of floods occurring season after season are being felt in many parts of Nigeria. This incident is expected to increase with much emphasis on the climate change situation. Flood events are not evenly distributed; some areas experience more frequent and severe floods than others (Oladokuni & Proverbs, 2016, Hirbayashe, 2013). The Northern area of Nigeria is noted to have experienced more flood incidents with associated implications than other regions (Umar & Gray, 2023). From 2011 to 2023, Nigeria's highest frequency of flooding showed that the North-west geographic zones had the highest record of more than 31 occurrences. North-central records 20 instances, and North-east had 19 instances (NBS, 2018, Umar & Gray, 2023). However, other regions in Nigeria are not left out of the flood menace. Agbonkhese *et al.*, (2014) pointed out that almost all the cities in the South-west region, including inland regions, have been greatly ravaged by flood cases. In the year 2011, the Nigerian national newspapers on August 29th, conveyed flood event cases that hit Ibadan after a five-hour intense downpour, with severe consequences on the environment, infrastructures, and loss of lives. The coastal region, such as Lagos, has the same history of flooded streets and homes, especially when there is heavy downpour, usually from June to September (Agbonkhese *et al.*, 2014; Oladokuni & Proverbs, 2016). Similarly, other states, which include Kogi, Benue, Niger, Plateau, Taraba, and parts of Kaduna in North-east, were among the inland states that suffered the most. The main causes are the overflow of the Niger and Benue Rivers, extended rainfall, and the discharge of surplus water from Cameroon's Lagdo Dam Oladokuni &

Proverbs, 2016). Coastal areas, river basins, and low-lying plains face higher flood risks (Umar & Gray, 2023). The Niger and Benue Rivers, for instance, are prone to seasonal flooding, exacerbated by heavy rainfall and dam releases (Ogunribido & Ogunribido, 2024). Coastal areas, particularly in the Niger Delta, face the dual threat of riverine flooding and rising sea levels, which contribute to more frequent and severe flooding events. However, the South-east region is noted to have fewer flood cases similar to the South-south zones (Umar & Gray, 2023). The first peak flood cases in the past years were recorded in 2012 in the country, with about 18 heavy occurrences; similarly, 2014 and 2016 flood incidences had fewer incidences (Ogunribido & Ogunribido, 2024). The next severe flood event was recorded in 2015 and 2017, having 17 occurrences respectively. 2018 and 2019, with 12 incidents each. Another peak flood incident was recorded in the year 2022. This was regarded as the worst ever in recent decades, with higher fatalities affecting almost all the states (Ogunribido & Ogunribido, 2024). This affected mostly the South-South region, such as Cross River, Delta, Bayelsa, and Rivers states. Anambra and Ebonyi states in the South-East, the Federal Capital Territory in North-Central, and Jigawa, Adamawa, and Yobe States. However, Bayelsa state was described as the worst-hit state with very high instances. There are quite a few severe instances of flooding in the years 2023 and 2024 affecting mostly the coastal regions, among others (Ogunribido & Ogunribido, 2024, Ishaya *et al.*, 2009).

Flash flood events

Contributing factors to the flooding scenario in some regions are the release of water from various Dams and other water bodies, which is usually known as a flash flood event. For instance, the Lagdo Dam in Cameroon was noted to have released continuous water on September 13, 2024, after heavy rainfall, which caused the River Benue and its tributaries to overflow, devastating villages in the North-eastern states of Kogi and Benue state (Ezenwajiobi, 2024). The Nigerian government had originally planned to build a second dam, the Dasin Hausa Dam in Adamawa State, to manage these overflows from Lagdo Dam, but the project was never completed. Similarly, the water discharge from the Oyan Dam in the 2012 flood event worsened the situation of

Attenuating stormwater runoff

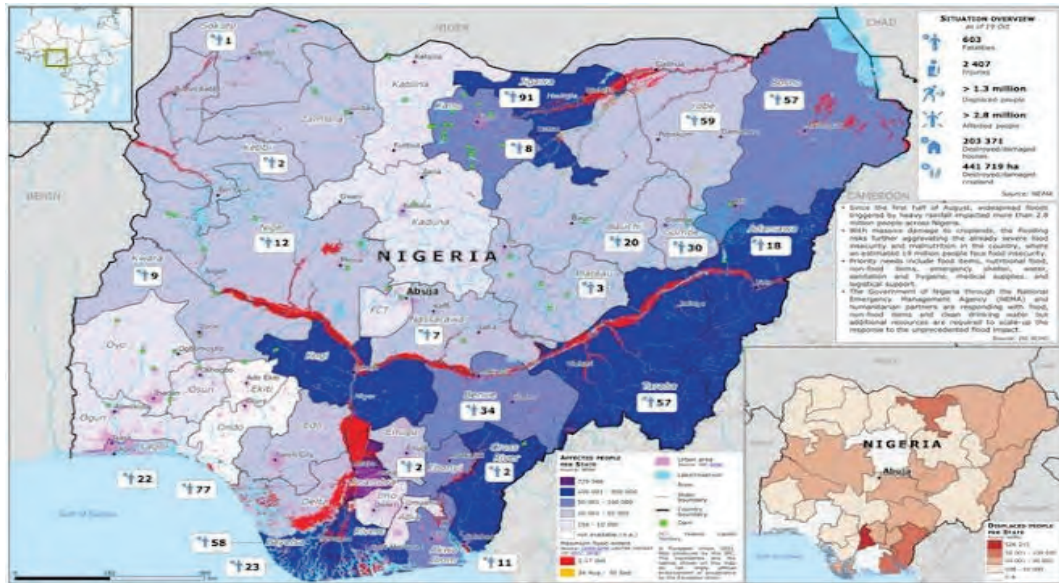


Fig. 1: Map Showing Vulnerable Areas in Nigeria (Ogunribido & Ogunribido, 2024).

the Ogun River, causing approximately 1000 people in the Lagos and Ogun States region of Nigeria to be displaced (Ezenwajobi, 2024). Flash flood is expected to persist, especially with settlements close to Dam locations, major rivers, and the riverine areas (Ogunribido & Ogunribido, 2024).

Runoff-inducing flooding

Flooding has emerged as a significant global threat, and Nigeria is particularly vulnerable to its devastating impacts. Most studies of literature have attributed increasing frequency and intensity of floods in Nigeria to a combination of factors ranging from geographical structures and land terrain, poor urban planning, climate change impact, rapid urbanization, uncontrolled deforestation, and lack of proper attention to environmental problems (Ornguze *et al.*, 2022; Brian 2021; Oladokun & Proverbs, 2016; Dalil *et al.*, 2015; Abaje, *et al.*, 2015; Hirabayashi, 2021, IPCC, 2014). Emerging discoveries that expand on our knowledge of recent causes of floods include groundwater extractions, increased plastic pollution resulting in drain blockages, and the microclimatic impact of land use change. However, as these factors remain valid for flooding occurrences, stormwater runoff's implications on flooding should not be overlooked. In this study, Rainfall runoff (storm water runoff) will be discussed as another major inducing

cause of flooding affecting the urban areas in Nigeria. Storm runoff is the excessive overflow from previous and impervious surfaces, such as roofs, driveways, pavements, sidewalks, and road infrastructure typical features of urban regions (Nagare & Supekar, 2024). The rapid growth of cities with a high concentration of impervious surfaces featuring variety of land coverings, including parking lots, buildings and roadways (Stransky *et al.*, 2010, Hirabayashi, 2021). These land coverings have a major impact on the urban hydrological cycle, noticeable in the reduction of natural methods of infiltration and evaporation with a significant increase in the volume of storm runoff (Bobbi *et al.*, 2014). Roxane *et al.*, (2024) pointed out that the permeable nature of Earth's surface in a natural system allows rainwater to seep in and replenish the groundwater table. However, the present-day experiences of water leakages from urban slopes and impervious surfaces are typically the cause of flooding and the notable rise in river water levels (Bobbi *et al.*, 2014; Roxane *et al.*, 2024; Stransky *et al.*, 2010). Managing stormwater in recent times should be given utmost consideration, especially in the midst of mounting population growth and the climate change situation, resulting in adverse consequences of the new hydrological circumstances of precipitation (Lina *et al.*, 2024, Nagare & Supekar, 2024). By 2050, it is projected

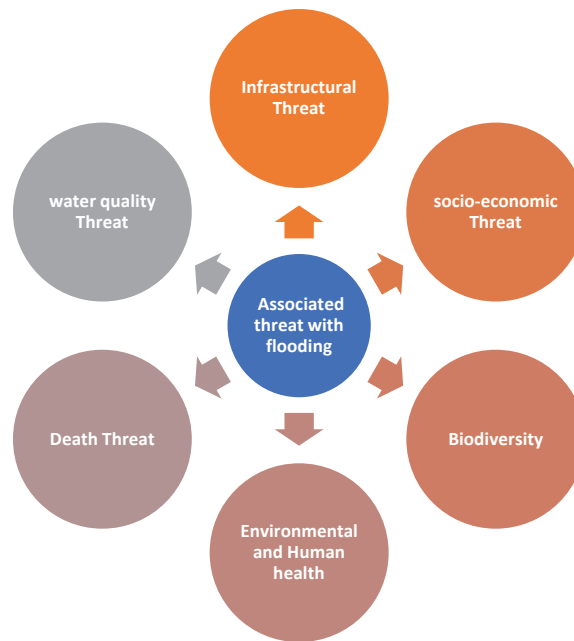


Fig. 2: Associated threat of flooding

that about 9 billion people will be on the planet, which would significantly alter the organization of urban regions. This would exacerbate the effects of rainfall and, in conjunction with anticipated storm runoff and flooding (Jusi *et al.*, 2020). The necessity to safeguard public health, well-being, and safety, as well as to shield property from flood dangers, will require attenuating and discharging stormwater from developments (Kristiina. 2020). Similarly, the obligation to protect nature's surroundings and the desire to offer the best strategies for managing runoff will be more needed. Stormwater attenuation has been observed to have negatively affected flood risk. However, the design flow chosen, the position of the development within a catchment, and the broader catchment characteristics are factors considered (Thomas *et al.*, 2024). Different methods of sustainable storm attenuation exist in developed nations ranging from Low Impact Development (LID), practiced in the United States of America (USA). The method focused on preserving natural areas and lowering impervious cover through site design (Bobbi *et al.*, 2014). Ciu *et al.*, (2021) pointed out that bioretention methods (Low Impact Development techniques) were demonstrated with proven results that delayed and decreased peak flows, allowing

the system to retain a larger runoff volume. Chan *et al.*, (2018) investigated the usage of a treatment train under Best Management Practice (BMP) for stormwater concerns, flooding, and runoff quality control in Kuala Damansara, Selangor, Malaysia. The techniques included a detention pond and a constructed channel ecological swale. The result proved that the long-term solution to stormwater problems, such as floods and runoff volume control, was the treatment train, an improved technology for capturing stormwater runoff.

Associated flood risk in Nigeria

Every year, the rainy season in Nigeria, starting from June, records an erratic degree of flooding. Varying havoc and damage have followed the annual flood incidence all over the country. From the report, the states most affected in 2022 are Adamawa, Borno, and Yobe states in the North-east region, the North central region includes Nasarawa state, Bauchi, Taraba, Benue, and Kogi. Others include Bayelsa state from South-south, Anambra from South-east, and Jigawa in the North-west (Ekpoh, 2015; Udoh, 2015 Evan, 2017; Abubakar, 2020). In recent years, floods have resulted in a considerable loss of lives and property, significant agricultural losses,

Table 1: Summary of associated flood risk in Nigeria (NEMA, 2022; IOM, 2022)

States	Number of Affected Persons	Number of displaced persons	Number of houses with partial damage	Number of houses totally damaged
Anambra	675,953	526,015	5,511	2,755
Kogi	206,562	200	-	-
Yobe	160,000	42,700	8,641	8,885
Adamawa	135,552	14,439	2,136	15,156
Benue	83,016	32,633	358	34
Borno	50,242	30,516	9,477	10,201
Jigawa	150,438	61,942	1,564	3,849
Bauchi	25,122	2,738	3,136	2,059
Nasarawa	34,827	22,040	381	1,689
Taraba	147,755	6,089	1,343	16,082
Bayelsa	38,442	-	25	34
Total	1,702,909	739,322	32,372	60,754

with an estimated 110,000 hectares of farmland ruined, resulting in food scarcity and price increase (Nkwunonwo *et al.*, 2016). Socioeconomic impacts are noticeable in exacerbating poverty and inequality in Nigeria. Vulnerable communities, particularly those in low-lying regions, are disproportionately affected. Fig. 2 exposed other associated flood threats in Nigeria. Moreover, reports from NEMA National Emergency Management Agency and (DTM) Displacement Tracking Matrix (DTM) flood flash reports from September 2022 state that 1,664,467 people across all the regions were affected. Moreover, shelters covering 60,720 were destroyed, while 33,542 shelters were nearly destroyed. Moreover, more than 600 individuals, including children, have died across the country (NEMA, 2022; IOM, 2022). Table 1 reveals an overview of the states in Nigeria affected by flooding.

Flood risk management

Advances in flood behavior and prediction have been informed by recent floods, with technologies like remote sensing, GIS, and flood modeling enhancing the accuracy of forecasts and the efficiency of early warning systems. These tools have strengthened disaster response efforts and guided better planning and risk management strategies (Oke *et al.*, 2023, Oladokun *et al.*, 2016). The need for improved policies and response mechanisms has been underscored by recent flood events, emphasizing the importance of timely and coordinated responses, resilient infrastructure, and the integration of scientific knowledge into flood management strategies (Oladokun *et al.*, 2016). These insights have

influenced both national and international efforts to improve flood preparedness and resilience (Oke *et al.*, 2023, Kundzewicz, 2014). Flood hazards and human response through adaptation, flood control, and protective measures. Adaptation involves actions taken to reduce or mitigate the impact of flood risks. Flood control focuses on modifying land use within a river basin to lower the likelihood of flooding (Ebhuoma *et al.*, 2021). Protective measures involve constructing physical barriers like river channelization, embankments, dykes, levees, flood diversion channels, and reservoirs to store floodwaters (Ward, 2015). Table 2 shows studies from several authors on suggested flood risk control in Nigeria. Flood problems have persisted despite all the effort put in place and various government policies to reduce the impact of flooding. Strategies suggested for flood control are still mostly found on an abstract basis. Nigeria is experiencing its worst seasonal flooding in recent years, impacting more communities, destroying homes, businesses, and vital public infrastructure like roads, bridges, and utilities (Nkwunonwo *et al.*, 2024). The worst of it all is loss of lives, loss of environmental quality, and habitat displacement. This destruction leads to business interruptions, loss of income, and increased expenses for repairs and reconstruction (Adesola *et al.*, 2024). Fig. 3 revealed the recent flood havoc in the Nigerian environment. The growing concern is that this flooding will exacerbate the country's already severe food insecurity and malnutrition crisis. At present, over 19 million people in Nigeria are suffering from extreme food insecurity, with more than 440,000 hectares of cropland partially or

Table 2: Suggested flood risk management

Study Focus	Suggestions	Sources
The study focused on curative and management strategies of flood in Nigeria	- Flood plain management Utilizing storm water run-off water for inter-basin reuse. - Construction of embankments in flood prone area to capture runoff. (1)	(1) Agbonkhese et al., 2014 (2) Oladokuni & Proverbs, 2016 (3) Ologunorisa, 2009 (4) Oluchi, et al., 2017
The study analyzed flood risk management and opportunities	embracing of sustainable integrated FRM system such as blue system and green infrastructures. (2)	(5) Bridge & Oguno, 2023 (6) Brian, 2021
The study focused on approaches for extenuation of flood related risk in Niger Delta, region	Flood reduction Schemes. Achievable through land-to-channel runoff phase and deforestation practices. (3)	(7) Adelekan, 2014 (8) Bridge & Oguno, 2023 (9) Ezezie et al., 2017
The study examined effective flood management system in Anambra state.	The authors suggested that dams should be constructed across river channels as well as wing dykes and afforestation practices. (4)	(10) Adefisoye, 2017 (11) Nwosu, 2014 (12) Echendu, 2023
The study investigated flood risk and coping strategies in one of the low-lying regions in Nigeria	The effective strategy recommended apart from policy suggestions was to develop water drainage channels to ease surface run-offs (5)	(13) Nkwunonwo et al., 2024 (14) Mafimisebi, 2024
The study examined flood risk impact and management practices in Nigeria	Ecological based solution such as vegetated banks to reduce runoff off, The use of porous paving material to allow infiltration of runoff and adoption of green roof technology to capture runoff at source. (6)	(15) Adesola et al., 2024
The study evaluated flood risk management by public and private agents in Lagos coastal region.	Management approaches suggested are more of structural and policy base with reverence to flood preparedness, the need for improved meteorological forecasts was recommended. (7)	
Flood risk, management and coping strategies in Cross river state was examined in this study.	Traditional drainage canals were the major method used to control flood risk while most residents depend on flood prediction by government agencies. (8)	
The study examined suitable flood management in six communities in Anambra state (South-east) regions	The recommended strategies include construction of artificial levees, wing dams, diversion spillways, and afforestation practices. (9)	
A study of flood management in Ekiti state (South- west) region.	Suggested solution from this study is the involvement of citizen" s participation and involvement in local communities to participate in flood management. (10)	
Nigeria's flood management prospects were the focus of this study.	Disaster management such as systematically observing and analysing disasters in order to enhance preparedness, mitigation, prevention, emergency response, and recovery procedures. (11)	
The study investigated efficiency of local methods for managing flood risks in Port Harcourt (South -south) region.	The study suggested eco-system restoration such as building urban forest to reduce storm water runoff within the local community. (12)	
The study examined the management of flood using ecosystem-based approach in Ogun state (South- south) region	The study offers a fresh perspective on how to strengthen community resilience, integrate environmental services into local FRM, and adapt traditional practices and resources for flood risk reduction. (13)	
Issues and strategies for flood management was the focus of the study	According to this study, a complete approach should be used to build urban infrastructure, enable more entrepreneurs to create and provide FRM solutions, and include FRM ideas and practices into the nation's educational programs. (14)	
The study examined the public health impact of the 2022 flooding event in Nigeria	Nature-based solution was recommended, such as understanding the role of wetlands, soil, marshes, and forests for the storage effect. (15)	

completely destroyed (Anabaraonye *et al.*, 2022). The Food and Agriculture Organization predicts that cereal production will likely be 3.4% lower than the previous year due to the floods, high production costs, and ongoing insecurity problem (Anabaraonye *et al.*, 2022). The advancements in technology that allow for monitoring and predicting floods, improving early warning systems, and enabling more effective

disaster response seem to be more abstract and less practical solutions. Seeking a better solution and a way out remains the only option. This review harnessed divers' sustainable solutions and natural local methods to tackle runoff-induced floods in affected regions in Nigeria. This is critically needed given the climate-changing impact and urbanization circumstances (Daniele & Vivian, 2020).

Attenuating stormwater runoff



Fig. 3: Recent flood cases with a) Adamawa state, b) Lagos state, c) Niger delta, d) Anambra state (Obianer, 2024; Olasunkanmi et al., 2024)

Sustainability target for 2030, sustainable development goal agenda SDG

The word sustainability has persisted as a long-term goal that focuses on the ability of society to grow and develop without exhausting or depleting the natural resources required for future generations to live. United Nations Commission (Brundtland Report, 1987) (Kulman & Farrington, 2010, Echendu, 2020). Sustainable development is defined as the process of “meeting the needs of the present without compromising the ability of future generations to meet their own needs (UN, 2016). This significant report lays out the fundamental characteristics and consensus surrounding the idea of sustainable development for all countries. The concept of sustainability is based on the idea that Earth’s natural resources are limited; therefore, supporting sustainable practices helps preserve a balance between the environment, economy, and equity (Maria, 2020). However, aligning with the United Nations Sustainable Development Goals SDGs target for 2030 will require a proactive step towards

achieving sustainable development and a better future for everyone. Attaining this goal will involve tackling many problems that humanity faces to guarantee economic growth, human well-being, and environmental preservation for both developed and developing nations by 2030 (Parry, 2018). Problems like flooding are creating consequential damage both to human life and the environment. The disparities in influence are explained by the fact that nations around the world have varying degrees of development with distinct difficulties (Echendu, 2020). Sustainable flood risk solutions touch on Agenda 11 of SDGs, a target that will be discussed under the subheading below.

SDG 11 (Sustainable cities and communities)

SDG 11 agenda aim at making cities and human settlements livable and to guarantee that human settlements are in the best possible condition for living, while having the least detrimental effect on other communities or environmental impact on natural elements (UNDP, 2016). Its primary goal is to meet the needs of the community’s most vulnerable

and impoverished individuals and to protect human settlements' security and integrity in the face of present climate change risks. (Wahab, 2017; UNDP, 2016). However, insight and knowledge about nature-based solutions for urban resilience with a greater focus on equality in city design for populations at risk should be included. Flooding poses a serious risk to accomplishing SDG 11, while communities that are vulnerable to flooding are not viable and livable, which usually results in fear of future cities and communities (Echendu, 2020). The urban poor in Nigeria are particularly susceptible because they lack most of the social protection and the capacity to recover from the effects of flooding (Oke *et al.*, 2023). Urban flooding is noted to have been caused by several variables, including climate change, fast urbanization, poor urban planning, deforestation, and a lack of concern for environmental problems. Inadequate solid waste management and poor water and wastewater infrastructure maintenance (Koop & van Leeuwen, 2017). Given Nigeria's rapid urbanization and population growth, more attention must be devoted to settlements and communities susceptible to flooding, which is presently the most frequent and severe environmental issue it faces, to create sustainable cities and communities (Echendu, 2020; Security, 2013). Sustainable practices in developed countries that have yielded positive results in attenuating runoff flow volume should be incorporated to reduce the impact of flooding in human settlements as an attainment of the SDGs 2030 agenda.

Incorporating sustainable solutions in flood-prone regions

Recent studies in the literature have begun

to pay more attention to the issue of sustainable management of water resources in relation to flooding and stormwater attenuation (Lapointe *et al.*, 2022). Flood risk management touches on several SDGs, including those about climate change, water management, resilient infrastructure, sustainable cities and communities, and the sustainable use of terrestrial ecosystems. Sustainability in flood control practices emphasizes proper and robust flood risk management (Owen, 2022). Sustainable flood risk management depends on the growth of information regarding the risk and likelihood of flood events, which will guide successful and resilient flood risk management techniques and enable the development of appropriate and effective policies and decision-making (Shah *et al.*, 2018). To incorporate a variety of flood risk perceptions into the decision-making process, sustainable flood risk solutions will necessitate broad community and stakeholder engagement. This will ensure proper adaptation and a full variety of flood risk perceptions in the decision-making process, especially from grassroots (Almoradie *et al.*, 2020). Fig. 4 revealed sustainable solutions to be applied in floodplain regions in Nigeria.

Sustainable drainage system (SUDS)

Sustainable drainage system is a widely accepted concept essential for runoff flow reduction, leading to sustainable and natural flood control with agreeable principles, especially for urban areas (Miklas, 2015). It is needed at this critical time to support the weakness of conventional drainage system functions because of the implications of urbanization and climate change (Qianqian, 2014). The impact of climate change has been broadly recognized as a

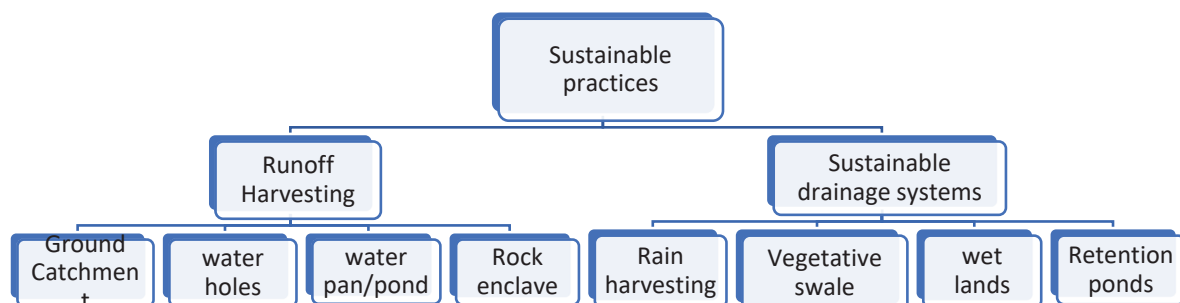


Fig. 4: Sustainable practices for flood control

universal issue affecting the global natural features, resulting in intense rainfall, accelerated urban water runoff, and flooding (Willems *et al.*, 2012). This situation has posed an enormous challenge to the available conventional drainage system, which was not designed for such storm runoff capacity. Ebele & Emodi, (2016) confirmed that the major cause of flooding remains in effectively addressing the root causes resulting from extreme weather events and heavy downpours, which have overwhelmed the existing drainage and runoff management systems, leading to devastating floods in various parts of the country. Sustainable Drainage Systems are envisioned to control surface storm runoff at a closer distance to where it falls, thereby encouraging a natural draining method at a closer spot (Ward, 2020, Daniele & Vivian, 2020). This will provide the chances of flood mitigation and a combination of water management functions. SUDS is of prodigious global importance, maintaining a beneficial tool for improvement of urban environment spaces, functioning to reduce the impact of flooding and forming a new management approach for sustainable cities (Rodriguez-Rojas *et al.*, 2017). Many developed countries, most particularly in Italy, the United Kingdom, the United States, and Asia countries have implemented the use of sustainable drainage systems to reduce runoff flow, advert the impact of flooding, and mitigate the climate change situation within the environment (Boluwatife, 2021). SUDS, purpose focuses on natural processes and methods that lower the catchment flow point and lessen runoff peak discharge. For instance, Coventry University conducted research on flood reduction using different kinds of SUDS methods, which include detention basin, green roof, decanting paved surface, and vegetated swales, used as an experimental study to control flood. However, the four adopted methods displayed positive responses in the reduction of runoff flow. However, swale recorded an effective reduction of storm water flow than others (Yiyang, 2024, Qiao *et al.*, 2018). This study authenticates the capacity of SUDS in reducing flood events and associated risk. Source control methods can be introduced in areas that are most vulnerable in Nigeria. This method includes detention basins, retention ponds, vegetative swales, and wetlands. It required identifying the low terrain areas that can accommodate the runoff flow, thereby preventing the peak accelerated drift to communities

and settlement. Fig. 5 displayed a few examples of the recommended method for applicability in the Nigerian environment.

Rain runoff harvesting (RWH)

Several studies from the literature have proven that flooded areas in urban catchment can be condensed up to 100% with the employment of rainfall harvesting techniques, even with a small amount of rainfall. However, nearly a 35% reduction of flooded areas can be achieved with severe rainfall events (Gabriele & Lorena, 2019, Paolo *et al.*, 2020). RWH is another sustainable method that performs a double function. It captures water from the source, reduces runoff flow, controls flooding, and supplies water for re-use purposes (Paolo *et al.*, 2020). It is usually done at a small scale in a few rural communities in Nigeria based on household capacity. However, household collection of rainwater looks insignificant to solve these flood-related problems using rain harvesting because of the recent rainfall intensity caused by climate change. Government input is needed to develop a larger rain harvesting hub, especially in various affected communities. In developed countries, rain harvesting techniques with the adoption of open surface catchment methods were successfully implemented along with small-scale irrigation projects for the riparian state in Africa. This was executed to support agricultural production (Mati, 2012). Campisano and Modica, (2017) explored the effectiveness of an RWH system installed to reduce peak flow during storm runoff events in Sicily, a small city in Southern Italy. The results disclosed that, dependent on the capacity of the tank and rainfall intensity and features, the installed RWH tank efficiently reduced the peak flow of rainfall in a multitude of storm events. Similarly, Teston *et al.* (2018) evaluated the outcome of RWH using several scenarios on flood reduction in Curitiba city (Southern Brazil), the outcome indicated a reduction of runoff peak flow. Rainwater harvesting (RWH) is the process of collecting rainfall runoff either through the roofs, ground surface, or rock catchment. Storage of rainwater is usually achieved using tanks, rocks in the catchment area, and reclaimed dams (Paolo *et al.*, 2020). Rainwater harvesting serves many purposes, ranging from domestic water use, industrial processes, and irrigation functions (Gabriele & Lorena, 2019). The goal of this study's

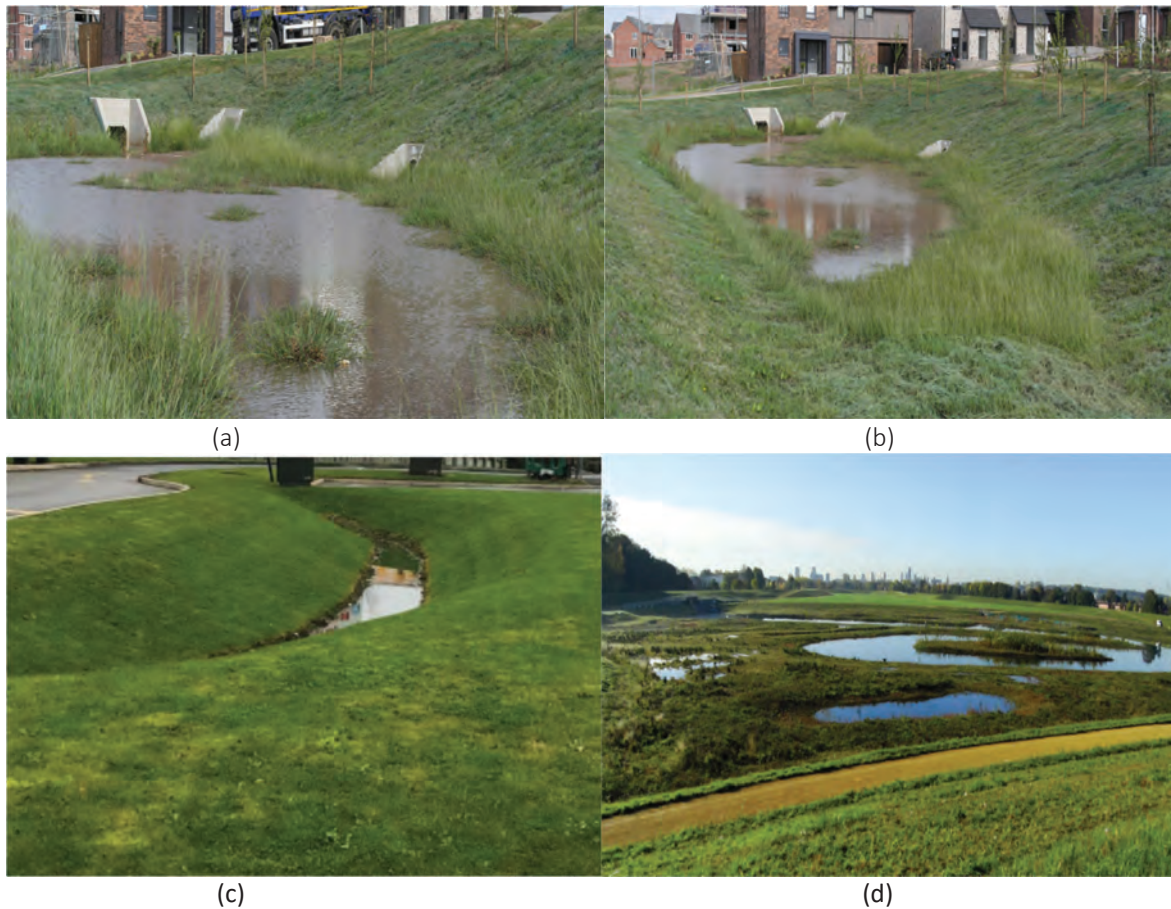


Fig. 5: SUDs practices showing SUDs practices. (Flood hub, 2021)

approach is to collect rainwater runoff from a collection point to lower peak flow, which typically causes environmental flooding. To lower the volume of runoff flow, the procedure may entail directing the roofs of every structure to a point where rainwater. However, it will involve some financial implications, which will prove a better result in the long run. Its potential as an option for water supply can also be harnessed for other purposes. Fig. 6 reveals the types of rain runoff harvesting methods practiced in developed countries. This is also explained using the following subheadings.

Ground catchment

Any kind of ground surface that provides surface runoff for water collection is referred to as a “ground catchment.” The surface can include roads, housing compounds, pasture plains, woodlands, rocky

areas, and other open land surfaces, both paved and unpaved. In terms of variations in the intake and outflow of water and other variables, naturally occurring catchments are typical examples of an open system (Ariwadun, 2020, Xinyao *et al.*, 2022). For micro ground catchments, the sizes could range from a few square meters to vast land areas and entire watersheds used for massive storage devices like dams. In locations without suitable roofing, runoff can be collected using small or micro-scale ground catchments, while greater runoff flows can be collected in larger catchments and stored for reuse for either irrigation or large-scale water sources (Xinyao *et al.*, 2022). Stefanus, (2012) stated that the catchment size significantly affects the relationship between rainfall and runoff and, in turn, the applicability of calculation techniques. For instance, the relationship between rainfall intensity

and soil infiltration rate is crucial in small catchments, whereas in big catchments, the amount of rainfall in proportion to the ground's capacity to store water is more significant (Brown et al., 2005). Ground catchments often have the advantage of collecting water from a broader area when compared to roof harvesting (Mati, 2012). This will be helpful, especially in flood-prone areas in Nigeria.

Water holes

Water holes are minor excavated ponds used to collect small amounts of water, mostly for domestic use in rural areas, livestock purposes, and occasionally for modest garden irrigation (Mati, 2012). They are extremely adjustable both spatially and temporally. They are frequently part of larger wetlands, such as a waterhole within a riverine wetland. In regions with a high-water table or where the soils are self-sealing, it is unlikely that you will experience seepage issues. waterholes are typically dug by hand in most cases (Hayward & Hayward, 2012). A residential compound's water hole is typically situated in the lower portion to take advantage of natural drainage and the potential for minimal earthwork. It is ideal for the catchment surface to be impervious. If at all feasible, the catchment area could be artificially prepared through soil conditioning or concrete pavement (Paolo et al.,

2020). Developed countries such as Queensland in Australia developed waterholes for diverse purposes, among which is retaining storm flow and reducing runoff (Zivee et al., 2020). The purpose here is engineered towards the reduction of runoff flow in flood-prone areas.

Rock enclave catchment

This is a ground catchment arrangement where a large rocky surface is utilized as a surface runoff source (Mati, 2012). The runoff is channeled to a storage tank or reclaimed facility. This should be considered in regions where the rock surface is dominant for capturing storm runoff and reducing the impact on communities. Rock catchments work well in places where there are large, irregular rock outcrops (Nissen-Petersen, 2006). This method of runoff catchment is noted with several distinctive features and gravity flow supplies. It is also regarded as a cost-effective method of rainwater runoff catchment system (Ogen, 2015). They exhibit high runoff coefficients because of the impervious surface nature of the rock, which speeds up the acceleration of water flow even with a limited amount of rain (Nissen-Petersen, 2006). The water derived from the rock catchment can be reused for other purposes that suit the nature of the water. Constructing a rock



Fig. 6: Rain harvesting methods (Mati, 2012).



Fig. 7: showing types of water pan/ pond with a) local water pan, b) retention ponds (Mati, 2012)

catchment can be done by community members as a form of participation towards reducing the impact of floods in the built environment.

Water pan/ponds

Excavated pans/ponds are small reservoirs that range in depth from one to three meters, typically dug off-stream with compacted banks surrounding them (Mati, 2012). The distinction is that ponds are built in areas with a high-water table or some groundwater contribution, whereas pans get all of their water from surface runoff (Chalov et al., 2016). Both pans and ponds are built to catch and hold runoff water from a variety of surfaces, including roadways, hillsides, rocky regions, and open rangeland. Pans and ponds are typically constructed near communities in industrialized nations, on grazing grounds as opposed to farmlands. When compared to surface or subsurface tanks, one benefit of pans and ponds is their ability to store a comparatively large volume of rainwater. Pans do not get groundwater contribution; they are entirely dependent on surface runoff (Chalov et al., 2016). Storm runoff can be reduced into ponds in flood-prone areas to lower the runoff flow. Both retention and detention ponds exist in sustainable drainage, functioning as pools filled with water that fluctuate in response to runoff and rainfall. They prevent erosion and flooding by collecting water and releasing it gradually (Lisetskii & Buryak, 2023). Retention ponds type of SUDs, are primarily used to enhance the quality of urban runoff and reduce peak stormwater runoff rates by temporarily retaining water after heavy storm. They can be made by

building embankments, excavating a new depression, or utilizing an already-existing natural depression (Zabolotnia et al., 2022). Fig. 7 shows the water pan and retention pond adopted in developed countries.

Required green infrastructure practices

Green infrastructure, according to the World Bank Group, aims at managing the effects of rainy weather while providing social, economic, and environmental advantages by utilizing natural processes (UFCOP, 2016, Maria, 2020). Apart from the earlier-mentioned green practices for immediate solutions, other green infrastructures can also be integrated as a long-term provisional solution. These practices include the following

Green/ Blue roof

Green roofs are flat or gradually sloping roofs with vegetation and a planting medium on top of the roof material. They help to retain runoff from the roof, thereby lowering peak flow at ground level (Kristiina, 2020). It is typically a filtering crust, drainage coating, waterproof membrane, thermal padding, and vapor control layer (Parry, 2018). It works to control climate change impact with a lot more advantages, such as lowering building temperature, cooling and heating requirements, enhancing air quality, prolonging roof membrane life, lessening the heat island effect, and using less water by reusing collected rainwater (Skjeldruma & Tore, 2017). Blue roof is also known as a non-vegetative type. They are designed to be retained on the surface or in specially premeditated trays. These surfaces or trays gradually release the

water using a flow-restriction device surrounding the roof drains. Green and blue roofs both lower the volume of stormwater runoff and peak floods; they also remove pollutants by absorbing and filtering them (Mohammed *et al.*, 2020; Parry, 2018).

Tree planting practices/afforestation

Studies from literature have constantly emphasized the need for tree planting given the current climate change situation ravaging the globe (Mercy Forest, 2014; Pataki *et al.*, 2021). By planting native trees or preserving existing ones, runoff can be slowed, captured, and stored in the canopy, and evapotranspiration can release water into the atmosphere (Pataki *et al.*, 2021). Additionally, the soil conditions created by tree roots encourage infiltration. Other benefits embedded in tree planting afforestation practices include, apart from reducing stormwater, temperature and noise reduction, absorption of carbon dioxide, accommodating urban wildlife habitat, providing shade for recreation and relaxation, promoting property values, and reduction in maintenance costs (Turner-Skoff & Cavender, 2019).

Tree box filter

Tree boxes, usually known as stormwater tree trenches, are usually joined by an underground trench, forming a row of trees within the soil featuring layers that help in storing and filtering stormwater runoff (Tobio *et al.*, 2014). They function effectively in parking lots and roadway spaces, with little room for stormwater management. The only disadvantage is the cost implication, especially for larger regions, because they work best for smaller sites or neighborhoods (Pataki *et al.*, 2021). Tree boxes are a particular kind of bioretention technique is They are engineered landscape techniques that use vegetation to filter or seep into stormwater runoff (Tobio *et al.*, 2014). These practices can be integrated into roadways and parking lots to attenuate storm runoff flow.

Potential Embedded in Sustainable Practices

Utilizing sustainable stormwater attenuation techniques is crucial to management and addressing several environmental issues, fostering resilience and sustainability in communities (Lina *et al.*, 2024). Studies from literature have identified lots of cost

benefits and potential it engages, such as reduced flood danger, better water quality, more biodiversity, and higher amenity values, among others (Bobbi *et al.*, 2014). For instance, the method of restoring wetlands, extending stormwater retention, and retrofitting stormwater ponds enhances water quality while lowering flood risks and peak flows United States Environmental Protection Agency has harnessed these potentials, pointing out that the major goal of stormwater attenuation is to improve water quality and decrease runoff (EPA, 2024). In Nigeria, this process of stormwater management can fit in as another means of water supply, especially for remote areas where water scarcity exists. To increase water efficiency and lower the demand for domestic water use. Several factors should be taken into account, such as water conservation and water demand management. Reducing water loss and creating substitute water sources. All users, from primary residential use to water for irrigation, stock watering, recreation, and aquatic habitat maintenance, must meet certain water quality criteria. Actionable steps towards achieving these embedded potentials will require conducting a baseline evaluation, such as assessing flood history, flood-prone areas, and significant stormwater channels. However, information on rainfall patterns and runoff volume will be valuable. Collaboration and partnership with external professionals and experts should also be incorporated, while policy integration involving grassroots governance and stakeholders will be of great importance. Funding sources needed for effective, actionable steps could accommodate budgetary allocations from the national or local governments, the Ministry of Infrastructure and Environment, international aids and grants, social responsibilities from corporate organizations, while real estate and housing developers may also be required by regulations to provide drainage infrastructure while initiating development.

Economic and policy barriers

Sustainable stormwater attenuation has proven to have yielded many advantageous results, especially in the developed countries where such exist; however, there are also financial and policy obstacles that should not be disregarded, especially in Nigeria. Execution of sustainable infrastructure for conceivable runoff attenuation, such as rain gardens

and detention basins, entails significant funding and investment; therefore, intending communities may witness limited financial support due to budget constraints. However, facilitating planned community involvement and private developers may oppose incorporating sustainable drainage systems (SuDS) due to perceived risks or lower immediate returns on investment. Similarly, policy hurdles and a lack of clear legislation that encourage or mandate sustainable stormwater management practices might be limited. Similarly, current zoning laws may not prioritize or allow for the incorporation of green infrastructure, especially in urban centers that have already experienced development.

CONCLUSION

This review assesses Nigeria's use of sustainable methods for stormwater runoff attenuation as a potential solution for flood impact reduction. The need arises due to the requirement for sustainable cities and settlements for everyone to meet SDG 11's target by 2030. Numerous SDGs, 2030 agenda, such as those related to climate change, water management, resilient infrastructure, sustainable cities and communities, and the sustainable use of terrestrial ecosystems, are touched upon by flood risk management. The review highlighted sustainable methods of attenuating storm runoff volume, with few practical examples practiced in developed countries. For instance, sustainable drainage systems and the source control methods, runoff harvesting/rain harvesting hubs, runoff ground catchment/water holes, rock enclaves, and water pans, among others. Government effort is urgently needed in practicality, not in abstract, towards achieving this target. However, in the broader framework of the SDGs' sustainability goal, improving our residential communities and environment remains essential; therefore, it demands a clarion call for all to participate, such as participation of stakeholders, including NGOs, the private sector, donors, politicians, religious organizations, philanthropists, institutional entities, and community participation. Moreover, Partnerships and collaborations in development also offer reliable and timely solutions for achieving the predetermined objectives. The terms partnership, collaboration, and other related terms like alliance, union, and networking. cooperation and work groups indicate a broad variety of interactions and

arrangements. The difficulties of flooding and its related effects can be lessened by a concerted, persistent, and resolute effort by all parties, including government organizations.

AUTHOR CONTRIBUTIONS

G.U. Fayomi performed the literature review. E.K. Onyari supervised the work. S.R. Funsho conceptualized the work. F.J. Odekunle investigates and reviews the work.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

BMP	Best Management Practices
DTM	Displacement Tracking Matrix
EPA	Environmental Protection Agency
FRM	Flood Risk Management
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LID	Low Impact Development
NBS	National Bureau of Statistics
NEMA	National Emergency Management Agency
NGOs	Non-Governmental Organizations
RWH	Rainwater Harvesting
SDGs	Sustainable Development Goals
SUDS	Sustainable Drainage System
UN	United Nations
UNDP	United Nations Development Programme

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