International Journal of Human Capital in Urban Management
(IJHCUM)

Homepage: http://www.ijhcum.net/

ORIGINAL RESEARCH PAPER

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

R. Venkatesh Kumar[1], A. Subanginidevi[1], D. Sivakumar[2,*], J. Nouri[3,4]

[1] *Department of Management Studies, Sri Vidya Mandir Arts and Science College, Uthangarai, Tamil Nadu, India*

[2] *Department of Agricultural Engineering, Kalasalingam Academy of Research and Education, Krishankoil, Tamil Nadu, India*

[3] *Department of Environmental Health Engineering, Tehran University of Medical Sciences, Tehran, Iran*

[4] *1137 Spectrum, Irvine, Orange County 92618 USA*

ARTICLE INFO

Article History:
Received 16 April 2025
Revised 09 June 2025
Accepted 19 August 2025

Keywords:
Agricultural supply chain
Cold storage
Digital innovation in farming
Infrastructure challenges
Technology adoption

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.

DOI: 10.22034/IJHCUM.2026.02.01

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
35	8	10

*Corresponding Author:
Email: *shri.sivakumar0307@gmail.com*
Phone: +91-9790973774
ORCID: 0000-0001-5228-0145

Note: Discussion period for this manuscript open until July 1, 2026 on IJHCUM website at the "Show Article.

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, Krishankoil, 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 (km^2), 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

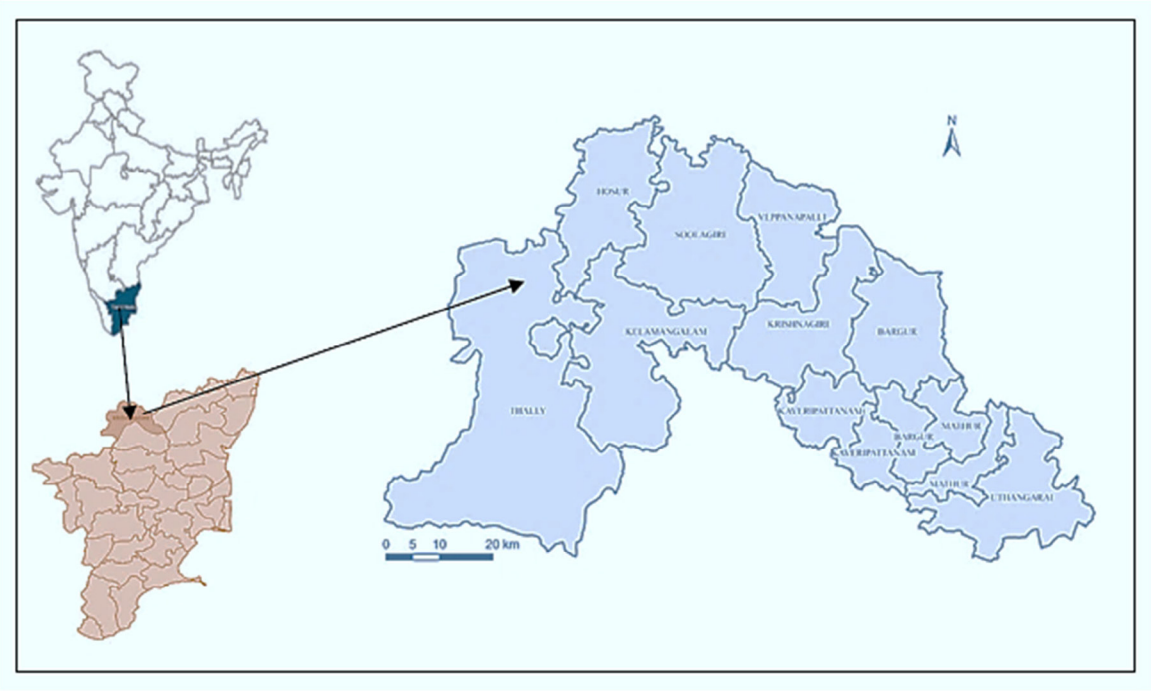

Fig. 1: Location map of Krishnagiri district (study area)

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

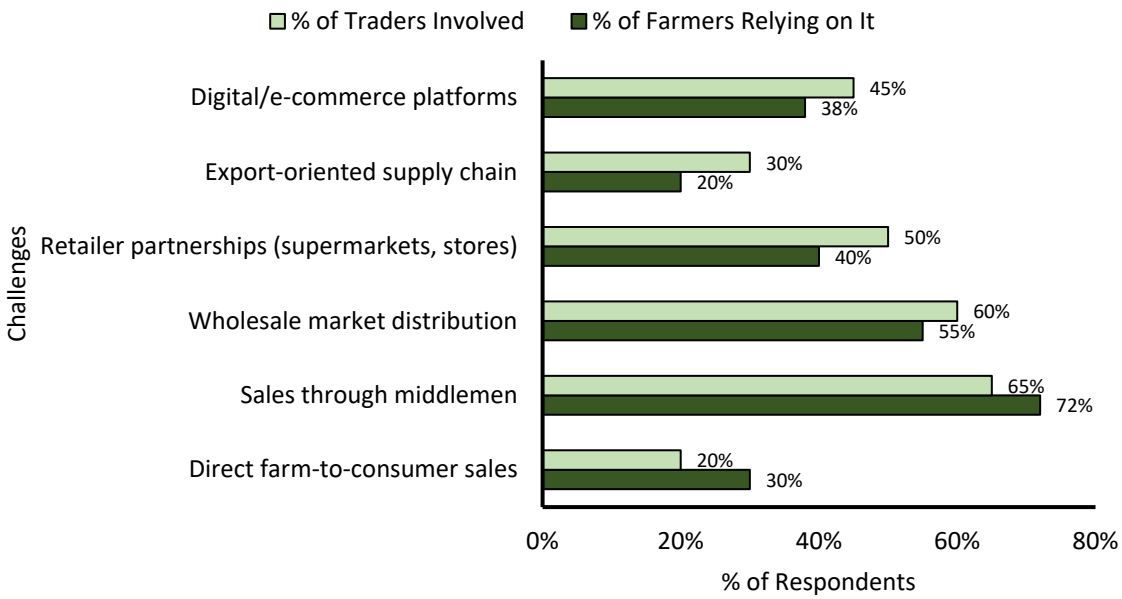

Fig. 2: Engagement of farmers and traders across various agricultural supply chain components

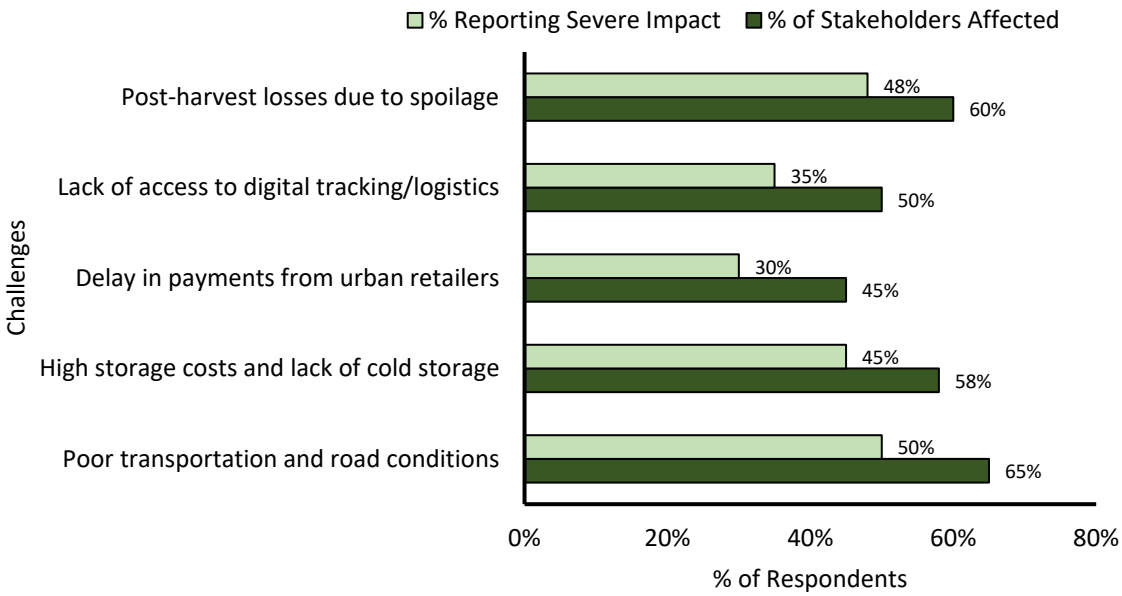

Fig. 3: Key storage, transportation, and distribution challenges in the mango supply chain

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%

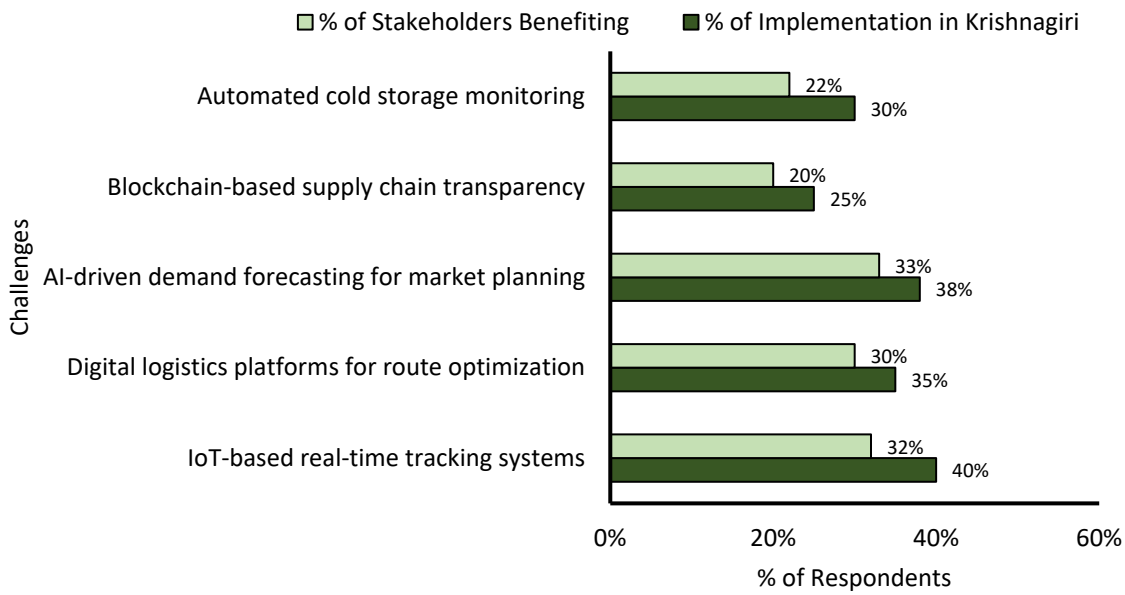

Fig. 4: Survey results on smart logistics and IoT adoption in Krishnagiri

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.

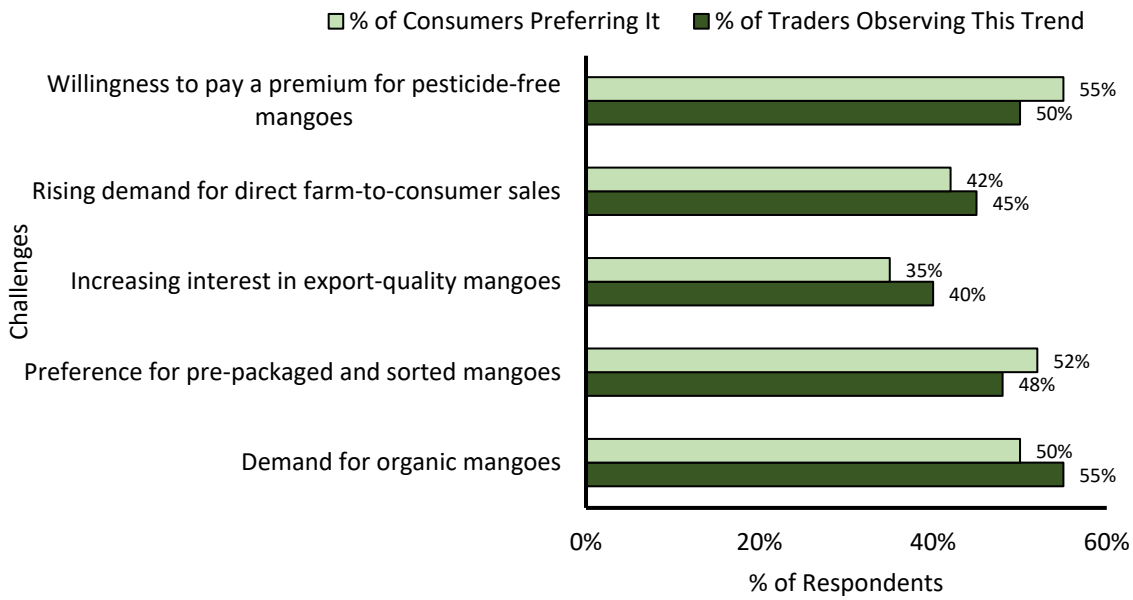

Fig. 5: Survey results on market trends and consumer preferences in mango distribution

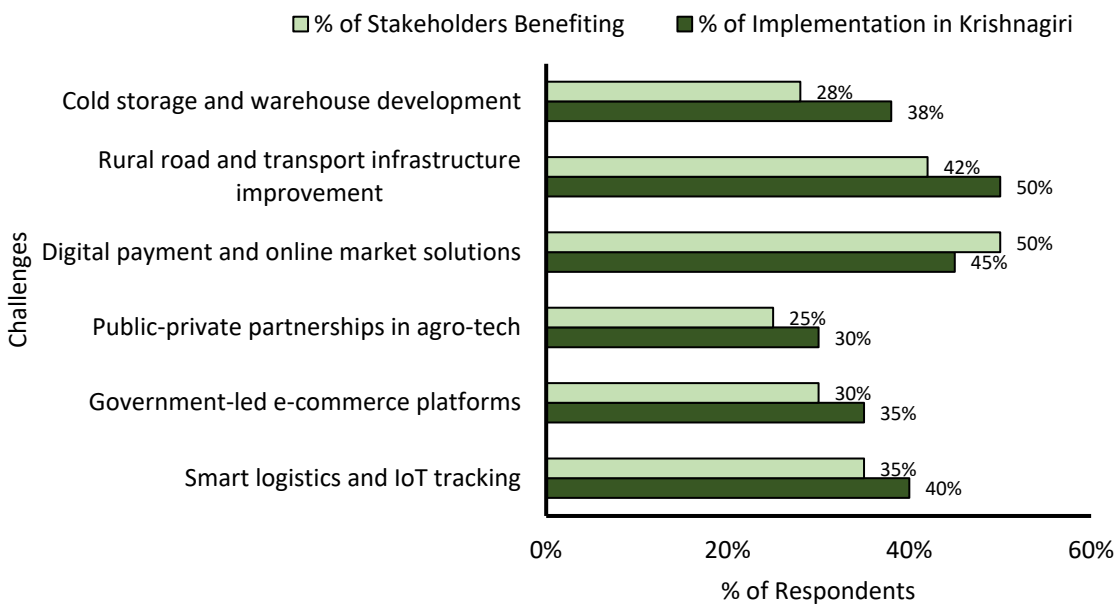

Fig. 6: Policy and Infrastructure Initiatives in the mango supply chain

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.

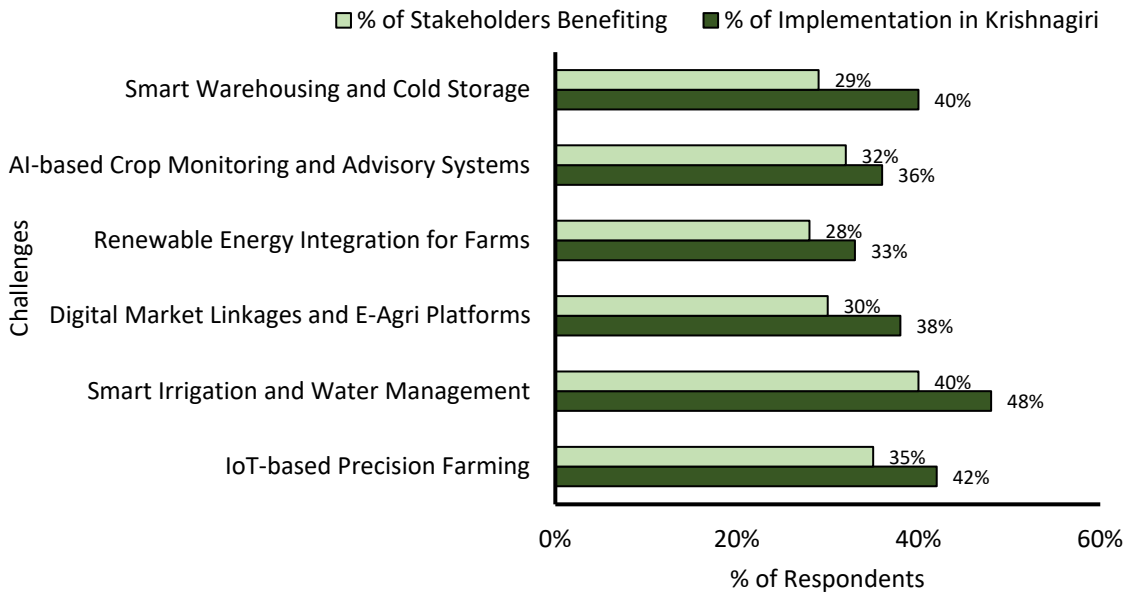

Fig. 7: Smart city initiatives and agricultural development in the mango supply chain

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,

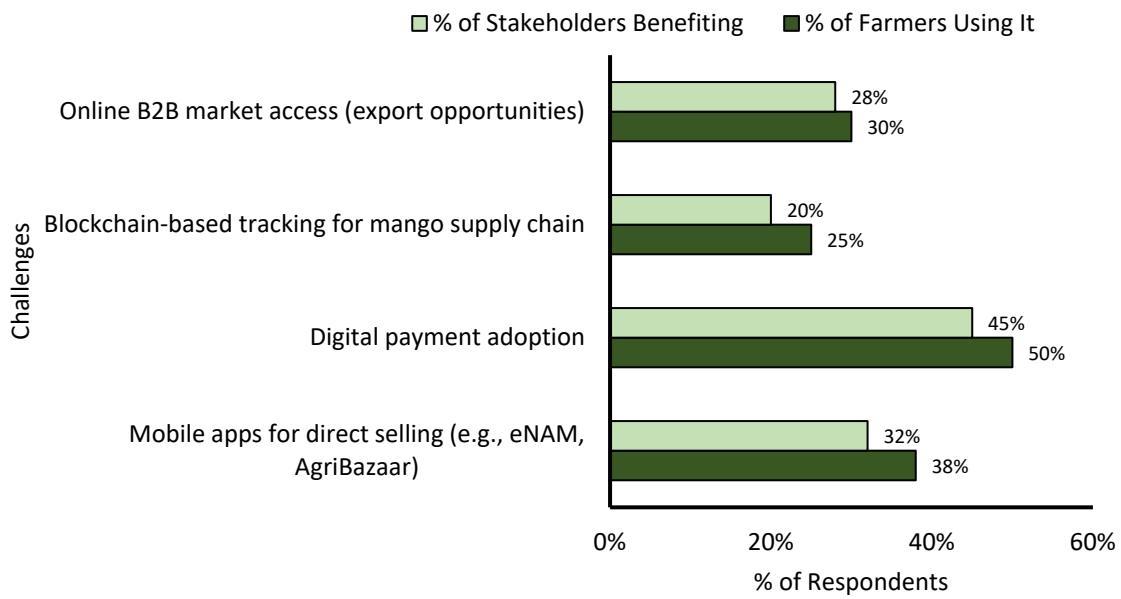

Fig. 8: Adoption of ICT-based market linkages and e-commerce solutions in the mango supply chain

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.

ACKNOWLEDGEMENT

The authors sincerely acknowledge and appreciate the unwavering support provided by Sri Vidya Mandir Arts and Science College, Uthangarai, Tamil Nadu, India, and Kalasalingam Academy of Research and Education, Krishnankoil, Tamil Nadu, India, throughout the research process. Special thanks to the Tehran University of Medical Sciences, Tehran, Iran, for their valuable collaboration and guidance. All institutions offered invaluable resources, facilities, and guidance that were instrumental in the success of this study. Their assistance allowed for effective data collection, thorough analysis, and the formulation of meaningful conclusions.

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.

PUBLISHER NOTE

Tehran Urban Research & Planning Centre (TURPC) takes a neutral position about claims on disputed territories, place names, international boundaries, jurisdiction in published maps, and institutional affiliations. TURPC is committed to retracting a paper after its publication if it becomes apparent that there are serious problems in its content, in terms of research and publication ethics (https://www.ijhcum.net/journal/process?ethics).

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
km²	Square Kilometers
LISS IV	Linear Imaging Self-Scanning Sensor IV
SPSS	Statistical Package for the Social Sciences

REFERENCES

Audate, P.P.; Fernandez, M.A.; Cloutier, G.; Lebel, A., (2018). Impacts of urban agriculture on the determinants of health: Scoping review protocol. JMIR Res. Protoc., 20(3): 1-14 **(14 pages).**

Barwal, P.; Sharma, S.; Bali, D.; Laishram, C.; Kashyap, P., (2022). Resource use efficiency and constraint analysis of mango cultivation in Kangra district of Himachal Pradesh. Indian J. Ecol., 49(5): 1736-1742 **(8 pages).**

Bogachov, S.; Kirizleyeva, A.; Mandroshchenko, O.; Shahoian, S.; Vlasenko, Y., (2022). Environmental sensitivity of flash flood hazard using geospatial technique Economic policy of Eastern European countries in the field of energy in the context of global challenges. Global J. Environ. Sci. Manage., 8(1): 1-16 **(16 pages).**

Camacho, A.; Alves, R.A.; De Smedt, F.; Van Keer, H.; Boscolo, P., (2021). Relations among motivation, behaviour, and performance in writing: A multiple-group structural equation modeling study. British J. Educ. Psychol., 91(4): 1456-1480 **(25 pages).**

Elangovan, M.; Arunachalam, P.; Krishnan, A., (2017). A Micro Level Study of Mango Producers: Socio-Economic Profile in Krishnagiri District, Tamil Nadu. Int. J. Manag. Dev. Stud., 6(4): 67-71 **(5 pages).**

Enthoven, L.; Van den Broeck, G., (2021). Local food systems: Reviewing two decades of research. Agri. Sys., 193: 1-14 **(14 pages).**

Hagos, A.; Dibaba, R.; Bekele, A.; Alemu, D., (2020). Determinants of market participation among smallholder mango producers in assosa Zone of Benishangul Gumuz region in Ethiopia. Int. J. Fruit Sci., 20(3): 323-349 **(28 pages).**

Hosseini, E.; Tajpour, M.; Lashkarbooluki, M., (2020). The impact of entrepreneurial skills on manager's job performance. Int. J. Hum. Capital Urban Manage., 5(4): 361-372 **(12 pages).**

Kiloes, A.M.; Azizan, F.A.; Checco, J.; Joyce, D.; Abdul Aziz, A., (2022). What do consumers want in fresh mangoes? A systematic literature review. Int. J. Food Sci. Technol., 57(3): 1473-1492 **(20 pages).**

Kiloes, A.M.; Joyce, D.; Aziz, A.A., (2024). Exploring the challenges and opportunities of mango export from Indonesia: Insights from stakeholder interviews. The Qual. Rep., 29(3): 811-830 **(22 pages).**

Kisumbi, C.K.; Mulwa, A.; Mbugua, J.M.; Kikwatha, R., (2024). Enhancing performance of mango farming projects through participatory project management. Int. J. Prof. Bus. Rev., 9(9): 1-20 **(20 pages).**

Kumar, A.; Singh, S.; Jaiswal, P., (2017). Ultra-high-density plantation of mango new technology for Increasing the income of the farmers. Indian Farmer., 4(5): 368-375 **(8 pages).**

Laili, N.; Djatna, T.; Indrasti, N.S.; Yani, M., (2024). Optimization of industrial symbiosis in coffee-based ecoindustrial park design. Global J. Environ. Sci. Manage., 10(2): 621-642 **(22 pages).**

Lauricella, M.; Emanuele, S.; Calvaruso, G.; Giuliano, M.; D'Anneo, A., (2017). Multifaceted health benefits of Mangifera indica L. (Mango): The inestimable value of orchards recently planted in Sicilian rural areas. Nutrients., 9(5): 525-538 **(14 pages).**

Le, T.D.; Viet Nguyen, T.; Muoi, N.V.; Toan, H.T.; Lan, N.M.; Pham, T.N., (2022). Supply chain management of Mango (Mangifera indica L.) fruit: A review with a focus on product quality during postharvest. Front. Sustainable Food Syst., 5: 799431 **(16 pages).**

Manikandan, P.; Suguna, K.; Saravanaraman, M., (2021). Population dynamics of defoliating insect pests of mango in the coastal agroecosystem of Tamil Nadu. Pest Manage. Horti. Ecosyst., 27(2): 196-200 **(5 pages).**

Pandey, P.; Irulappan, V.; Bagavathiannan, M.V.; Senthil Kumar, M., (2017). Impact of combined abiotic and biotic stresses on plant growth and avenues for crop improvement by exploiting physio-morphological traits. Front. Plant Sci., 8(4): 1-15 **(15 pages).**

Qanti, S.R.; Reardon, T.; Iswariyadi, A., (2017). Triangle of linkages among modernising markets, sprayer–traders, and mango-farming intensification in Indonesia. Bull. Indonesian Eco. Stud., 53(2): 187-208 **(22 pages).**

Ramu, M.S.; Gaddi, G.M.; Sadhana, H.S.; Umesh, K.B.; Nayana, H.N., (2023). Cultivation challenges: Farmers realities in mango production and marketing with an agro-eco-tourism twist. Int. J. Stat. Appl. Math., 8(6S): 1347-1351 **(6 pages).**

Ravindran, K.; Chandan A.C.; Sivakumar, D.; Inayath Ahamed S.B.; Dhanabalan, T.; Kumaresan V., (2024). Urban Management and Sustainable Business by Entrepreneurs. Int. J. Hum. Capital Urban Manage., 9(3): 413-428 **(15 pages).**

Roy, S.; Rajkumar, B.; Misra, A.K., (2018). A pilot study for area-wide management of fruit fly in mango for the central gangetic plain. J. Eco-friendly Agric., 13(2): 68-71 **(4 pages).**

Sacramento, N.J.J.; Geges, D., (2020). Producers' cooperative in agro-eco-tourism development: The case of the Guimaras mango growers and producers development cooperative (GMGPDC) in Guimaras, Philippines. J. Human Ecol., 9(1): 93-123 **(21 pages).**

Sandhu, N.; El-Gohary, H., (2023). Unveiling the impact of psychological traits on innovative financial decision-making in small tourism businesses. J. Knowledge Eco., 14(3): 2284-2317 **(34 pages).**

Santhakumar, S.; Ravichandran, S.; Venkatraman, R.; Manimaran, S., (2019). Economic analysis of mango marketing in Krishnagiri District of Tamil Nadu. Indian J. Agric. Mark., 33(3s): 83-91 **(9 pages).**

Sathiyamurthi, S.; Subbarayan, S.; Ramya, M.; Sivasakthi, M.; Gobi, R.; Qaysi, S.; Praveen Kumar, S.; Lee, J.; Alarifi, N.; Wahba, M.; Youssef, Y., (2024). Advancing agricultural land suitability in urbanized semi-arid environments: insights from geospatial and machine learning approaches. ISPRS Int. J. Geo-Inf., 13(12): 436 **(23 pages).**

Schubert, A.L.; Hagemann, D.; Voss, A.; Bergmann, K., (2017). Evaluating the model fit of diffusion models with the root mean square error of approximation. J. Math. Psychol., 77: 29-45 **(17 pages).**

Sharma, B.; Tripathi, S.; Dhara, P.; Kumari, P.; Meena, S.; Kumari, R.; Kumar, A., (2017). Comparative study of mango-based agroforestry and mono-cropping system under rainfed condition of West Bengal. Int. J. Plant Soil Sci., 15(2): 1-7 **(7 pages).**

Subanginidevi, A., (2025). Promoting agile supply chain management for exporting mangos from Tamil Nadu: Opportunities and challenges. Expanding Oper. Through Agile Princ. Sustainable Pract., 143-166 **(24 pages).**

Tajpour, M.; Hosseini, E.; Mohammadi, M.; Bahman-Zangi, B., (2022). The effect of knowledge management on the sustainability of technology-driven businesses in emerging markets: The mediating role of social media. Sustainability, 14(14): 8602 **(15 pages).**

Tengsetasak, P.; Tongkoom, K.; Yomkerd, J.; Susawaengsup, C.; Khongdee, N.; Chatsungnoen, T.; Dangtungee, R.; Bhuyar, P., (2024). Sustainable Strategies for Fresh Mangosteen: Adapting to Climate Challenges. Earth Syst. Environ., 1-19 **(19 pages).**

Thippeswamy, N.; Yogish, S., (2023). Geographical perspective of mango production in Karnataka. Int. J. Sci. Develop. Res., 8(2): 444–446 **(3 pages).**

Thirumurugan, R.; Kundhavai, S.; Sivakumar, D.; Inayath Ahamed, S.B., (2024). Analysis of the 2023 flood scenario for urban disaster management from a strategic management perspective. Int. J. Hum. Capital Urban Manage., 9(4): 715-734 **(20 pages).**

Wardhan, H.; Das, S.; Gulati, A., (2022). Banana and mango value chains. Agricultural value chains in India: Ensuring competitiveness, inclusiveness, sustainability, scalability, and improved finance, 99-143 **(45 pages).**

Xie, C.; Gao, Y.; Zhong, Y.; Zhao, Z., (2024). Impact of digital agro-technology services on technical efficiency and income of small-scale farmers: Empirical study from mango production in China. Agric., 14(12): 2143 **(16 pages).**

Zahra, S.C.; Anggrainy, A.D.; Mohd-Zaki, Z.; Bagastyo, A.Y., (2024). Food waste reduction strategies in composting and recycling centers based on material flow analysis. Global J. Environ. Sci. Manage., 10(SI): 167-180 **(14 pages).**

HOW TO CITE THIS ARTICLE

Venkatesh Kumar, R.; Subanginidevi, A.; Sivakumar, D.; Nouri, J., (2026). Integrating smart technologies and sustainable infrastructure in the mango supply chain management for urban resilience. Int. J. Hum. Capital. Urban Manage., 11(2): 213-240.

DOI: 10.22034/IJHCUM.2026.02.01

URL: https://www.ijhcum.net/article_728546.html