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ORIGINAL RESEARCH ARTICLE

Challenges in residential biomedical waste disposal and urban governance for sustainable public health management

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ABSTRACT

BACKGROUND AND OBJECTIVES: This study investigates the disposal practices of residential Bio-Medical Waste and the challenges faced by urban local bodies in managing such waste in Himachal Pradesh, India. With a notable rise in home-based healthcare, especially post-COVID-19, households are generating increasing amounts of waste from activities such as self-medication, chronic illness management, and the use of disposable medical items and personal protective equipment. Despite this trend, most households mix Bio-Medical Waste with general municipal waste due to limited awareness, the absence of segregation systems, and a lack of designated disposal facilities. This poses significant risks to public health, particularly for waste workers and the broader community, and strains municipal waste management infrastructure. Urban authorities, constrained by inadequate policies, insufficient infrastructure, and limited financial and technical capacity, struggle to address this emerging challenge.

METHODS: The study utilized a mixed-methods approach, including household surveys, field observations, and stakeholder interviews across Himachal Pradesh state and the urban local bodies of various districts. In this study, the regression analysis and factor analysis tools are used to achieve the research objectives

FINDINGS: The results revealed that an urgent need for clear policy frameworks, as 72% of ULBs lacked specific guidelines for residential Bio-Medical Waste, and no penalties for improper disposal in 85 percent of cases. Public education, dedicated Bio-Medical Waste collection systems, staggering 68 percent of surveyed households admitted to mixing Bio-Medical Waste with general garbage due to a lack of awareness (42%), absence of dedicated bins (35%), convenience (23%), households found it easier to dispose of Bio-Medical Waste with regular trash and health risks to workers engaged in municipal solid waste management in urban areas, 89% of workers are encountered to Bio-Medical Waste daily, with 62% reporting injuries (needle-sticks, infections), in 28% of cases, no formal training or personal protective equipment was provided, and only 10% of workers are aware of the hazards of Bio-Medical Waste.

CONCLUSION: The research provides valuable insights for policymakers and urban managers to design more resilient and inclusive Bio-Medical Waste management strategies for sustainable urban health governance.

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INTRODUCTION

Bio-Medical Waste (BMW) management has been extensively examined in institutional settings such as hospitals and clinics, while residential BMW remains significantly under-researched, particularly in developing countries like India, where home-based healthcare is expanding rapidly (Olusunmade, 2019; WHO, 2022). Global research highlights severe public health and environmental risks associated with improper BMW disposal, including infection transmission from contaminated sharps, pharmaceutical leaching into groundwater, and occupational hazards for waste handlers (Samad *et al.,* 2019; Vinti *et al.,* 2021; Sharior *et al*., 2023). The BMW Management Rules (2016) provide a comprehensive regulatory framework targeting institutional sources while explicitly excluding household-generated BMW (Alzghoul *et al*., 2022). This regulatory omission has created a significant governance gap amid a growing prevalence of self-administered medical care, dialysis, and chronic disease management, all of which generate considerable quantities of BMW in residential areas (CPCB, 2020; Dutta and Jinsart, 2020). Studies in metropolitan cities such as Mumbai and Delhi report indiscriminate disposal of residential BMW, including used syringes, expired medicines, soiled dressings, and personal protective equipment, into Municipal Solid Waste (MSW) streams. The lack of source segregation and public awareness contributes to this co-disposal, increasing health and environmental hazards (Dehal *et al.,* 2022). This practice elevates the risk of needle-stick injuries, antimicrobial resistance, and environmental pollution through plastic and pharmaceutical waste (Samad *et al.,* 2019; Khosla *et al.,* 2022). Research in Kerala found that 68% of households disposed of BMWs unsafely due to inadequate risk awareness and the absence of structured collection systems (Samad *et al.,* 2019). Himachal Pradesh faces additional challenges owing to dispersed settlements, mountainous terrain, underdeveloped Urban Local Body (ULB) infrastructure, and limited policy compliance (Sharma and Acharya, 2019). Transportation barriers and the lack of treatment facilities make effective residential BMW management more difficult compared to urban areas. Several studies have confirmed the link between improper household waste disposal and public health outcomes, with risks including respiratory diseases, infections, and vector-borne illnesses increasing due to the mixing of BMW with general MSW (Mohammadi *et al.,* 2024). The Coronavirus Disease 2019 (COVID-19) pandemic further intensified these risks, yet post-pandemic evaluations have largely neglected the implications of increased BMW generated in residential settings (Teymourian *et al.,* 2021; Dehal *et al.,* 2022). International best practices, including Japan's and Germany's enforced segregation protocols and Brazil's decentralized health posts, demonstrate effective models for household-level BMW management. These include color-coded bins, pharmaceutical return systems, and community drop-off centers (Sharma *et al*., 2023; Silva *et al.,* 2022). Despite their success, such systems face contextual challenges in India due to low municipal capacity, weak enforcement, and limited citizen participation (CPCB, 2020). The role of informal waste workers in handling mixed waste is also inadequately addressed. Studies report high occupational risks due to a lack of protective equipment and training (Agarwalla *et al.,* 2017; Kavitha and Mohan, 2019). Effective local governance is essential for addressing these challenges. Municipal policies, public education, and civic participation significantly influence waste management outcomes (Oladejo *et al*., 2024). Most studies emphasize metro cities, ignoring the distinctive challenges of hilly states like Himachal Pradesh. Existing literature focuses predominantly on institutional BMW and urban-centric contexts. Studies by Devi *et al.,* (2019), Samad *et al.,* (2019) have examined residential BMW mixing with MSW in metropolitan areas such as Delhi and Mumbai. These studies do not account for the topographical, logistical, and governance challenges present in hilly states. Sharma and Acharya, (2019) highlight these issues in Himachal Pradesh but lack an integrated assessment of behavioural, infrastructural, and policy-level factors. Few studies have examined post-pandemic shifts in household BMW generation or the long-term public health consequences of improper disposal in residential contexts (Teymourian *et al.,* 2021). International models have been discussed in isolation (Sharma *et al*., 2023; Silva *et al.,* 2021), but their contextual applicability to Indian ULBs, particularly in low-resource or geographically dispersed areas, remains underexplored. Additionally, the role of informal waste pickers, despite being critical to urban waste management, is often mentioned without actionable frameworks for training, safety, and integration into formal systems (Agarwalla *et al.,* 2017; Kavitha and

Mohan, 2019). This study addresses these gaps by focusing on residential BMW management in Himachal Pradesh's ULBs. It integrates infrastructural analysis with policy and behavioural insights, evaluates the adaptability of global models in local settings, and includes the informal sector within the governance discourse. This comprehensive approach contributes new perspectives to the discourse on sustainable urban health management in ecologically sensitive regions. The objectives of this study are as follows:

(i) To investigate the generation and disposal practices of residential BMWs in urban households across selected ULBs in Himachal Pradesh, particularly in the context of increased home-based healthcare following the COVID-19 pandemic;

(ii) To examine the institutional, infrastructural, and policy-level challenges faced by ULBs in managing residential BMW in geographically challenging and resource-constrained environments;

(iii) To analyze public awareness, household behaviour, and barriers to proper segregation, including the use and availability of dedicated disposal mechanisms;

(iv) To assess the occupational exposure and health risks faced by municipal sanitation workers due to the improper handling of mixed BMW, including gaps in training, availability of protective equipment, and hazard awareness;

(v) To apply statistical tools such as regression analysis and factor analysis to identify the key determinants influencing household disposal behaviour and municipal management effectiveness;

(vi) To recommend context-specific, inclusive, and policy-relevant interventions aligned with the Swachh Bharat Mission (SBM) and Sustainable Development Goals (SDGs), aimed at strengthening urban BMW governance in ecologically sensitive regions.

The study on residential biomedical waste disposal and urban governance challenges was conducted in January 2025 at Lovely Professional University, Punjab.

METHODS AND MATERIALS

Study area

This study focuses on residential BMW management within urban Himachal Pradesh through a stratified selection of five ULBs, such as Shimla, Solan, Dharamshala, Mandi, and Bilaspur. These ULBs represent a range of geographic, climatic, and demographic conditions that influence BMW's generation and management practices. Shimla (31.1048° N, 77.1734° E), the state capital, is situated at an elevation of approximately 2,200 meters and experiences a temperate highland climate with cool summers and snowy winters, along with seasonal tourist influx and space constraints. Solan (30.9090° N, 77.0960° E), located at around 1,300 meters, has a subtropical highland climate with mild summers and growing pharmaceutical activity contributing to mixed waste streams. Dharamshala (32.2190° N, 76.3234° E), positioned at 1,450 meters, receives high rainfall and experiences significant seasonal variation in population due to tourism, impacting waste volume and flow. Mandi (31.7088° N, 76.9326° E), at an elevation of 800 meters, lies in a transitional zone between rural and urban development, with a humid subtropical climate and moderate rainfall affecting waste collection logistics. Bilaspur (31.3320° N, 76.7531° E), the lowest among the selected ULBs at around 670 meters, has a subtropical climate with warm summers and limited institutional capacity, situated near the environmentally sensitive Gobind Sagar Lake. These geographic and climatic factors directly influence BMW generation, storage, and handling efficiency, making them essential for evaluating public health risks and sustainability in urban waste systems.

Research design

The research design captures multiple dimensions critical in understanding residential BMW disposal practices and challenges faced within urban settings (Fig. 1). The selection criteria include administrative hierarchy, healthcare infrastructure, waste management capacity, and geographical representation (Ajbar El Gueriri *et al*., 2023). Administrative hierarchy reflects the inclusion of ULBs with varying governance levels, ranging from state capitals to smaller municipalities, enabling comparison across different institutional capacities. Healthcare infrastructure, indicated through the number and type of medical facilities such as hospitals, clinics, and pharmaceutical units, represents the scale of BMW generation within each ULB (Olusunmade, 2019). Waste management capacity considers the presence and nature of BMW treatment systems, including common, partial, shared, or absent facilities, offering insight into operational

preparedness. Geographical representation ensures spatial diversity across Himachal Pradesh, including hill stations, transitional settlements, and industrial zones, each presenting distinct environmental and demographic pressures. This comprehensive framework supports a detailed analysis of systemic gaps in BMW handling and enables the development of context-specific recommendations in urban waste governance. Table 1 provides a comparative overview of five selected ULBs in Himachal Pradesh, detailing population size, healthcare infrastructure, BMW processing capacity, and key urban challenges. From Table 1, it may be observed that Shimla, with a population of 230,000, has 3 hospitals and 28 clinics, supported by a common BMW processing facility. The city faces major constraints related to high tourist influx and limited urban space, impacting consistency in waste handling and treatment. Solan, with 160,000 residents, includes 2 hospitals and multiple pharmaceutical units. The city employs only partial BMW treatment, with significant risk arising from the mixing of industrial and BMW. Dharamshala, supporting 150,000 individuals through 1 hospital and 15 clinics, lacks a dedicated BMW treatment facility. Seasonal waste surges, likely influenced by tourism cycles, place additional pressure on existing waste infrastructure.

Fig. 1: Research design for ULBs

Further, it may be noted from Table 1 that Mandi, with a population of 120,000 and supported by one hospital and ten clinics, shares BMW treatment resources with surrounding areas. This urban area remains in a transitional phase from rural to urban conditions, presenting difficulties in scaling waste systems and institutional capacity. Bilaspur, with 80,000 residents, includes 1 hospital and 5 clinics and operates without any form of BMW treatment. The city exhibits limited institutional capability, restricting effective BMW control. The comparison reveals substantial differences in infrastructure and BMW management across ULBs. Higher population or healthcare presence does not ensure sufficient waste processing capacity. Cities with tourism, spatial constraints, or industrial mixing face a heightened risk of mismanagement. Public health and environmental protection remain vulnerable without targeted investment in treatment facilities, improvement in residential waste practices, and institutional strengthening within smaller ULBs.

Rationale for site selection

The selection of study sites across Himachal Pradesh is guided by the need to capture the diverse urban experiences influencing BMW management. By incorporating a mix of municipal classes, geographical terrains, and governance structures, the study aims to provide a comprehensive understanding of the systemic strengths and challenges within the state's urban waste landscape (Omo and Hassan, 2024). This approach ensures that findings are grounded in representative, real-world conditions that affect policy implementation and service delivery across varied urban contexts.

i. *Representative sampling:* It covers Class I (Shimla) to Class III (Bilaspur) towns. Includes tourist hubs and industrial towns, and balances hill stations and valley cities.
ii. *Urban management focus:* Varied implementation of Swachh Bharat Mission, different levels of municipal budget allocation, and contrasting public-private partnerships
iii. *Geographical considerations:* Altitude variations (300m to 2200m above sea level), Road connectivity challenges, Seasonal accessibility issues, and settlement patterns.
iv. *Urban governance context:* All sites share common institutional frameworks like the HP Municipal Corporation Act, State Pollution Control Board oversight, and varied implementation of BMW Rules (2016), Solid

Table 1: Selected ULBs and characteristics

ULB	Population (2021)	Healthcare Facilities	BMW Processing	Urban Challenges
Shimla	230,000	3 hospitals, 28 clinics	Common facility	Tourist influx, space constraints
Solan	160,000	2 hospitals, Pharma units	Partial treatment	Industrial waste mixing
Dharamshala	150,000	1 hospital, 15 clinics	No dedicated BMW	Seasonal waste surges
Mandi	120,000	1 hospital, 10 clinics	Shared facility	Rural-urban transition
Bilaspur	80,000	1 hospital, 5 clinics	No treatment	Limited ULB capacity

Table 2: ULB waste management capacity

Parameter	Shimla	Solan	Dharamshala	Mandi	Bilaspur
Waste Staff (per 1000 people)	4.2	3.1	2.8	2.3	1.5
BMW Collection Frequency	Daily	3x/week	Weekly	Biweekly	Monthly
Segregation Compliance	65%	48%	52%	38%	22%
Treatment Access	Yes	Partial	No	Shared	No

Waste Management (SWM) Rules (2016), and Swachh Bharat Mission guidelines.

Urban BMW governance in Himachal

ULB resource allocation patterns, service delivery mechanisms, and urban-rural waste flows shape the governance of urban waste in Himachal Pradesh. This stratified approach enables comparative analysis of urban waste governance while accounting for geographical and demographic diversity across the state's municipal landscape. The management of residential BMW in urban Himachal Pradesh presents a complex challenge that requires examination through multiple theoretical lenses. This study integrates urban governance theory, systems thinking, and risk perception theory to develop a comprehensive framework for understanding the persistent gaps in BMW management (Deepak *et al*., 2021). Urban environmental governance theory provides the primary lens for analyzing the institutional dimensions of BMW management. The theory highlights how multi-level governance structures often create implementation gaps in waste management systems. In Himachal Pradesh's urban context, this manifests through fragmented responsibilities between ULBs, the State Pollution Control Board, and central government schemes like Swachh Bharat Mission. These governance challenges are particularly acute for residential BMW, which falls outside the purview of existing BMW Management Rules (2016) that primarily regulate institutional waste generators (Alzghoul *et al*., 2022). Table 2 provides comparative insights into the BMW management capacity of selected ULBs across Himachal Pradesh. From Table 2, it can be noted that there is an uneven distribution of waste management resources and service standards, with Shimla having 4.2 waste staff per 1,000 people and daily BMW collection, showing the highest segregation compliance (65%) and full access to treatment. In contrast, Bilaspur has only 1.5 staff per 1,000 people, a monthly collection, low segregation compliance (22%), and no access to treatment. Other towns like Solan and Dharamshala fall between these extremes, with varying degrees of service frequency and infrastructure. This disparity underscores the fragmented and localized nature of urban BMW governance, contributing to systemic gaps and inconsistent risk mitigation across the state.

Network governance theory further explains how the absence of clear nodal agencies leads to coordination failures among stakeholders - municipal workers, healthcare providers, waste pickers, and households. This theoretical perspective helps explain why ULBs struggle with residential BMW despite having mechanisms for institutional waste, as the current governance architecture lacks provisions for household-level medical waste streams that have emerged prominently in the post-pandemic era. The systems theory perspective offers crucial insights into the technical and operational dimensions of BMW management. Viewing urban waste systems as complex adaptive systems reveals how the introduction of res-

idential BMWs creates new feedback loops that destabilize existing waste management infrastructure. The theory helps explain several observed phenomena: first, how the mixing of BMW with MSW creates systemic contamination risks throughout the waste value chain; second, why geographic constraints in hilly urban areas amplify transportation and treatment challenges; and third, how informal recycling networks inadvertently become disease transmission pathways. The systems perspective is particularly valuable for understanding threshold effects, for instance, how tourist influx in cities like Shimla and Dharamshala periodically overwhelms waste management capacity during peak seasons. This theoretical approach suggests that solutions must address the entire waste system rather than isolated components, emphasizing the need for decentralized treatment options and robust monitoring mechanisms. Risk society theory provides the third critical lens for examining the socio-behavioural aspects of BMW management. The theory's concept of "manufactured risks" perfectly encapsulates how the medicalization of households, through increased self-care, chronic disease management, and post-pandemic practices, has created new risk profiles that existing systems are ill-equipped to handle. Three risk dimensions emerge prominently: health risks for sanitation workers handling mixed waste, environmental risks from improper disposal, and social risks from unequal exposure to hazards (Gutberlet and Uddin, 2017). The theory helps explain the paradox between risk production and risk perception - while household BMW generation has increased dramatically, risk awareness remains low among urban residents. This disconnects between risk creation and risk acknowledgment creates significant barriers to behavioural change and policy compliance. The intersection of these theoretical perspectives reveals why conventional approaches to BMW management fail when applied to residential waste streams in urban Himachal Pradesh. Governance theories explain the institutional voids, systems thinking clarifies the operational breakdowns, and risk theory illuminates the socio-cultural dimensions (Liedong *et al.*, 2020). Together, they suggest that effective solutions must simultaneously address: (1) policy gaps through regulatory reforms that explicitly include residential BMW, (2) systemic constraints through appropriate technological interventions, and (3) behavioural gaps through targeted awareness campaigns. The theoretical integration also highlights the need for context-specific solutions that account for Himachal's unique urban geography - the predominance of hill towns, seasonal population fluctuations, and dispersed settlement patterns that differ markedly from plains-based urban models. This theoretical framework has important implications for both research and practice. For researchers, it provides a multidimensional approach to studying urban waste challenges in mountainous regions. For policymakers, it suggests the need for integrated strategies that combine governance reforms, technological solutions, and community engagement. The framework also helps identify key leverage points for intervention, such as improving waste segregation at source (systems approach), strengthening municipal capacity (governance perspective), and enhancing risk communication (risk theory). By grounding the study in these complementary theoretical foundations, the research can generate insights that are both academically rigorous and practically relevant for urban waste management in Himachal Pradesh and similar mountainous regions facing comparable challenges.

Data collection

A mixed-method research design structured the empirical foundation for assessing residential BMW management across urban Himachal Pradesh. This design captured both generator- and manager-level perspectives through integrated household surveys, stakeholder interviews, and field observations. The aim was to triangulate behavioural patterns at the household level with institutional capacity, policy gaps, and on-ground operational practices. Five ULBs were selected based on population characteristics, healthcare infrastructure, and waste generation

profiles, ensuring spatial, administrative, and demographic diversity for a comprehensive analysis (Banal and Abad, 2025).

Household surveys and stakeholder interviews

A mixed-method research design was adopted to comprehensively explore residential BMW disposal practices and the institutional challenges faced by ULBs in Himachal Pradesh (Soyler *et al*., 2025). Data collection involved three key components:

i. Household surveys: Structured questionnaires were administered to households across selected ULBs. The survey captured information on the frequency and type of BMWs generated, awareness of associated health risks, current disposal practices, and the extent of reliance on municipal services. Particular focus was placed on households engaging in self-care practices such as insulin injections, Personal Protective Equipment (PPE) use, and chronic disease management.

ii. Stakeholder interviews: Semi-structured interviews were conducted with key stakeholders, including ULB officials, sanitation supervisors, waste workers, representatives of the State Pollution Control Board, and Non-Government Organizations (NGOs) engaged in urban health and waste management. These interviews aimed to identify policy implementation gaps, infrastructure constraints, and inter-departmental coordination issues.

iii. Field observations: On-site observations were carried out at ward-level waste collection points, segregation units, and temporary disposal zones. These observations provided real-world insights into operational practices, segregation effectiveness, and occupational health risks for sanitation workers.

Five ULBs were selected based on population size, healthcare infrastructure presence, and municipal waste generation patterns (Banal and Abad, 2025). The data collection period spanned from March to August 2024.

Analytical framework for urban waste management

An integrated analytical framework was developed to assess the behavioural, institutional, and public health dimensions of residential BMW management (Deepak *et al*., 2021). This framework comprised the following components:

i. Household behaviour analysis: Descriptive statistical analysis was used to interpret household-level survey data, focusing on patterns of awareness, segregation practices, and disposal behaviour.

ii. Institutional capacity assessment: A Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was employed to evaluate the operational and policy capacities of ULBs. The assessment considered administrative efficiency, resource allocation, regulatory enforcement, and workforce training.

iii. Public health risk mapping: A qualitative risk exposure matrix was created to assess the vulnerability of waste handlers and sanitation workers to improperly disposed of BMW. This matrix was informed by interviews, field data, and public health guidelines.

iv. Sustainability gap identification: The findings were mapped against the targets of Sustainable Development Goals (SDGs) 3 (Good Health and Well-Being) and 11 (Sustainable Cities and Communities). Gaps in awareness, collection infrastructure, inter-agency collaboration, and financing were highlighted to inform future policy directions.

Addressing the complexities of residential BMW disposal and challenges faced with ULBs across Himachal Pradesh, India, involved the development of a comprehensive "*Analytical framework for urban waste management*". This framework integrates multiple analytical tools and methodologies, assessing current practices, identifying gaps, and proposing actionable strategies supporting sustainable waste governance. It comprises four key components: household behaviour analysis, institutional capacity assessment, public health risk mapping, and sustainability gap identification. This holistic approach enables understanding of the BMW issue from both the generator (household) and manager (ULB) perspectives, supporting informed recommendations promoting sustainable urban waste management.

Household behaviour analysis

The objective involved understanding patterns, awareness, and practices of households regarding BMW disposal. Structured household surveys across selected ULBs focused on types and quantities of

Table 3: SWOT analysis of ULBs in managing residential BMW

Category	Details
Strengths	Presence of a dedicated workforce specialized in waste management; availability of fundamental waste management infrastructure.
Weaknesses	Absence of specific policies targeting residential BMW management, inadequate specialized training programs for waste handlers, and constrained financial resources limiting operational capacity.
Opportunities	Potential for strategic collaborations with non-governmental organizations and private sector entities; scope for enhancing public awareness and community engagement initiatives regarding BMW hazards.
Threats	Escalation in BMW volumes due to increased prevalence of home-based healthcare practices; heightened risk of public health crises resulting from improper BMW handling and disposal (Samadi Foroushani *et al*., 2024).

BMW generated, awareness levels about associated health and environmental hazards, current disposal methods employed, and dependence on municipal waste services. Descriptive statistical techniques analyzed survey responses, highlighting prevalent behaviours and identifying areas with limited awareness. Findings revealed a significant portion of households mixing BMW with general waste, indicating poor segregation practices and limited understanding of health and environmental risks linked to improper BMW disposal (Rao *et al*., 2018).

Institutional capacity assessment

Evaluation focused on the readiness and capability of ULBs in managing residential BMW effectively. Semi-structured interviews were conducted with key stakeholders, including ULB officials, sanitation workers, and representatives from the State Pollution Control Board. A SWOT analysis examined existing infrastructure and resources, policy enforcement gaps, resource limitations, potential areas for improvement, external support opportunities, and emerging threats. Strengths identified include a dedicated workforce and basic waste management infrastructure. Weaknesses involve inadequate BMW-specific policies, a lack of specialized training for waste handlers, and insufficient financial resources. Opportunities arise from potential collaborations with NGOs and the private sector, alongside growing public awareness campaigns. Threats include rising BMW quantities due to increased home-based healthcare and risks of public health crises (Ajbar El Gueriri *et al*., 2023; Samadi Foroushani *et al*., 2024). Table 3 summarizes this SWOT analysis, highlighting key factors influencing the ULBs' capacity to manage residential BMW effectively.

Table 3 outlines the internal strengths and weaknesses within the current management framework, such as the presence of a dedicated workforce and infrastructure, alongside gaps like a lack of specific policies and training. It also highlights external opportunities, including potential partnerships and awareness campaigns, and threats such as increasing waste volumes and public health risks, all of which shape the effectiveness of BMW management by ULBs.

Public health risk mapping

The objective involved identifying and visualizing areas at heightened risk due to improper BMW disposal. Field observations combined with geospatial data collection facilitated the identification of unauthorized dumping sites and locations with frequent waste-related complaints. Geographic Information System (GIS) technology was utilized to generate detailed maps illustrating the proximity of waste disposal sites to residential zones, the density of unauthorized dumping locations, and incidence rates of waste-related health issues reported by local health centers (Jangre *et al*., 2022). Findings revealed multiple unauthorized BMW dumping sites situated near densely populated residential areas, with a clear correlation between improper BMW disposal practices and increased occurrences of diseases such as dengue and respiratory ailments. Fig. 2 illustrates the spatial risk assessment of unauthorized BMW disposal across urban settlements in Himachal Pradesh, categorized into high-risk (red), medium-risk (orange), and low-risk (yellow) zones. From Fig. 2, it can be noted that high-risk areas, particularly near Shimla and Solan, exhibit significant governance challenges in BMW handling, whereas medium-risk zones, including Mandi and Kullu, show moderate

concerns related to waste treatment infrastructure and regulatory oversight. The low-risk region indicates relatively effective BMW management systems. Major urban centers such as Mandi, Shimla, Dharamshala, Solan, and Kullu are distinctly marked to contextualize systemic gaps within the broader waste governance framework. The map integrates a scale (0–50 km) and orientation markers for spatial accuracy, reinforcing the need for field validation through epidemiological surveys and institutional assessments to develop targeted waste management interventions.

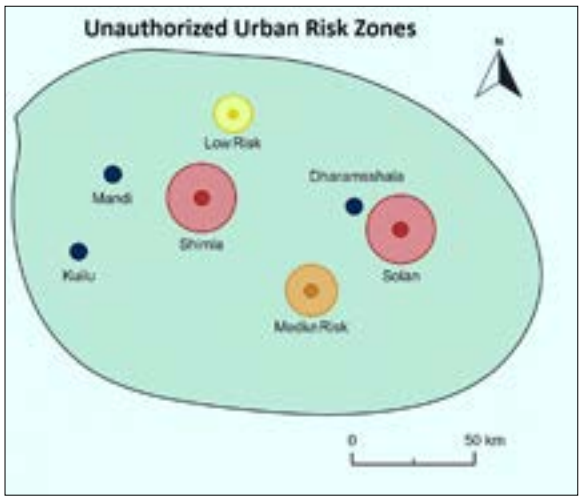

Fig. 2: GIS mapping of high-risk areas for BMW-related health issues

Sustainability gap identification

The objective focused on pinpointing critical gaps hindering the achievement of sustainable BMW management practices. Benchmarking involved comparing current local practices against national and international standards for BMW management. Stakeholder workshops engaged community members, health professionals, and waste management experts to gather diverse insights on perceived challenges and potential solutions. Findings revealed significant policy gaps, including the absence of clear guidelines and regulations specific to residential BMW. Infrastructure deficiencies were evident in the lack of specialized collection and treatment facilities at the municipal level. Financial constraints manifested as limited budget *al*locations for waste management programs, resulting in inadequate service delivery (Singh *et al*., 2022). Additionally, community engagement was low, with minimal public participation in waste segregation and disposal initiatives. Fig. 3 evaluates the multidimensional influences shaping residential BMW disposal within urban environments, emphasizing administrative hierarchy, healthcare infrastructure, waste management capacity, and geographical representation.

From Fig. 3, it may be noted that the administrative hierarchy enables comparison of ULBs across governance levels, facilitating institutional benchmarking for BMW regulation. Healthcare infrastructure assesses medical facility density, including hospitals, clinics, and pharmaceutical units, to quantify BMW generation and disposal requirements. Waste management capacity examines available treatment mechanisms categorized as common, partial, shared, or absent to determine operational preparedness and systemic inefficiencies. Geographical representation ensures spatial diversity by incorporating hill stations, transitional settlements, and industrial zones, each contributing unique environmental and demographic pressures. Collectively, these dimensions provide a structured approach to identifying governance gaps and optimizing urban BMW management interventions.

RESULTS AND FINDINGS

Building upon a multi-tiered methodology encompassing household surveys, stakeholder interviews, field observations, geospatial analysis, and benchmarking exercises, the results and discussion section synthesizes key findings related to residential BMW management across urban Himachal Pradesh. Drawing from data collected across five ULBs, the analysis examines critical aspects of public disposal behaviour, operational capacity, health risk exposure, and regulatory limitations. This integrated approach highlights how infrastructural gaps, policy ambiguities, limited awareness, and institutional fragmentation influence current waste management outcomes within the residential sector.

Current residential BMW disposal practices in urban households

The investigation into residential BMW disposal practices across urban centers in Himachal Pradesh, based on household surveys (n=800) and stakeholder interviews (n=42), reveals substantial inefficiencies and behavioural inconsistencies. A significant proportion of households engaging in self-care activities, including insulin administration, wound management,

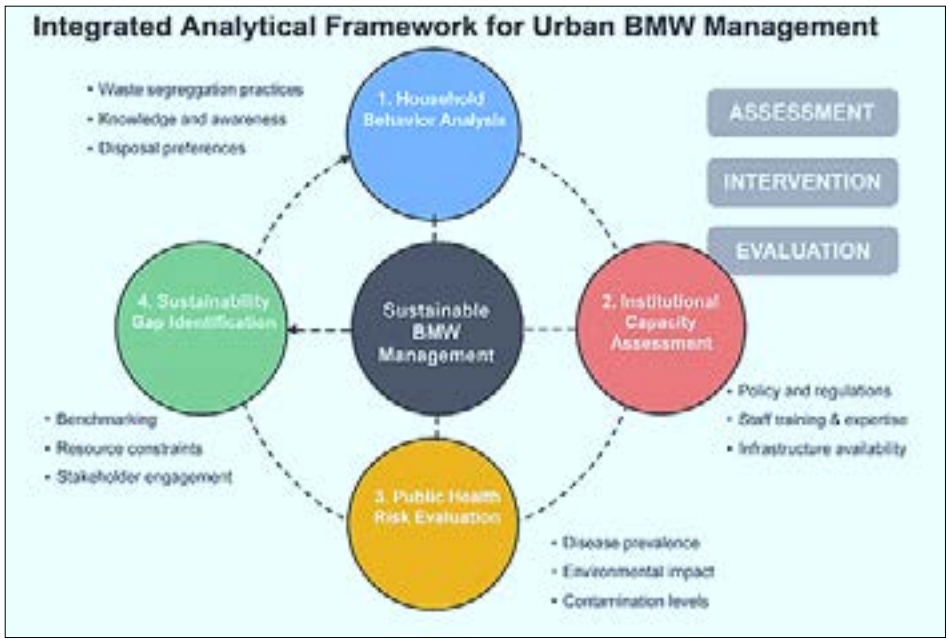

Fig. 3: Integrated analytical framework diagram

and personal protective equipment usage, lack access to safe and structured disposal mechanisms. Biomedical materials, such as used sharps, soiled dressings, and expired pharmaceuticals, are frequently discarded alongside general household waste, contributing to cross-contamination and increased health risks. Awareness of BMW-related hazards remains low, with limited adoption of segregation practices and widespread reliance on informal methods such as open disposal or flushing. Field observations confirm the absence of designated residential BMW collection infrastructure at municipal waste aggregation points and reveal that municipal sanitation workers, often operating without protective gear or specialized training, are exposed to hazardous materials during manual waste sorting. Stakeholder feedback further indicates a regulatory gap, as existing BMW Management Rules (2016) largely exclude decentralized sources such as households, leading to operational ambiguity at the ULB level (Alzghoul *et al.*, 2022). This is compounded by inadequate public outreach initiatives, minimal budgetary support, and fragmented inter-agency coordination, collectively impeding effective BMW governance. Samad, *et al.,* (2019) documented that 68.5% of households in Kerala disposed of medical waste through regular solid waste channels, only 10.2% used containment methods, and 15.8% admitted to open burning or flushing. Devi *et al.,* (2019) highlighted that more than 60% of urban respondents across four cities lacked awareness of BMW rules, 76% had not received municipal instructions, and 64% disposed of sharps unsafely. Compared to these studies, this investigation offers a broader and more operationally grounded understanding by integrating both behavioural evidence from a large household sample and institutional insights from municipal staff, while also capturing field-level infrastructural gaps and policy implementation barriers. The dual-layered data approach, inclusion of hill ULBs with topographical and logistical constraints, and real-time observation of municipal vulnerabilities make this study more comprehensive in scope and practical relevance, offering novel, replicable insights into residential BMW management beyond the descriptive focus of earlier research.

Residential BMW disposal challenges

The study reveals significant challenges in residential BMW disposal across urban centers of Himachal Pradesh, with 68% of surveyed households reporting that they routinely mix BMW, such as used syringes, expired medications, and PPE, with general household garbage. The three most frequently cited reasons include lack of awareness regarding BMW

Table 4: Prevalence and drivers of BMW mixing across ULBs

ULB	% Households Mixing BMW	Primary Reason	Common BMW Items Discarded
Shimla	58%	No separate bins	Syringes, expired drugs
Solan	72%	Lack of awareness	PPE, soiled dressings
Dharamshala	65%	Tourist waste influx	Medicine strips, gloves
Mandi	70%	No ULB guidelines	Used masks, bandages
Bilaspur	75%	No collection system	Blood test strips, vials

segregation rules (42%), absence of dedicated collection bins provided by ULBs (35%), and the perceived convenience of discarding BMW with regular domestic waste (23%). These behaviours point toward widespread knowledge deficits and infrastructure limitations across municipal jurisdictions. Table 4 presents the prevalence and drivers of BMW mixing across ULBs. From Table 4, it may be found that BMW mixing practices are most prevalent in smaller urban centers such as Bilaspur (75%) and Mandi (70%), where enforcement of BMW segregation norms remains weak and dedicated collection systems are absent. In contrast, Shimla, with comparatively better service infrastructure, records a lower but still substantial mixing rate of 58%. Solan shows the second-highest incidence (72%), largely attributed to a lack of public awareness. Tourist-intensive regions such as Dharamshala face seasonal spikes in BMW generation and mixing, complicating waste stream management. Across all ULBs, the commonly discarded biomedical items include syringes, expired medications, PPE, and soiled materials, underscoring both household health risks and the strain placed on general waste disposal systems. These findings indicate an urgent need for targeted public education campaigns, infrastructure investment, and localized enforcement mechanisms tailored to the specific contexts of each municipality.
The annual report of CPCB (2020) identified that only 40.2% of BMWs across urban India were being treated or disposed of through authorized channels, with non-bedded healthcare sources such as households and clinics contributing significantly to untracked BMW generation. The report further noted that 27 out of 35 state pollution control boards failed to ensure compliance with the BMW Management Rules (2016) among smaller ULBs. CPCB (2020) also highlighted the surge in unregulated household waste, particularly during the COVID-19 quarantine and treatment phases, recommending separate collection protocols for items like masks, gloves, and disinfectant containers, which were largely absent across surveyed ULBs. Devi *et al.*, (2019) observed that even institutional setups like hospitals reported 23% of their BMW entering general municipal bins due to segregation failure and poor internal monitoring, revealing a systemic pattern that has since extended into decentralized residential sources. The convergence of current field data with national reporting reinforces the critical gap between policy design and enforcement, especially within municipalities lacking robust institutional capacity and public engagement mechanisms.

Role of informal waste pickers in urban areas

Interviews with 10 frontline waste handlers across five ULBs revealed significant vulnerabilities in BMW management at the operational level. Fig. 4 illustrates the major health risks encountered during BMW handling in urban areas. It outlines common exposure pathways such as direct contact with infectious materials and needle-stick injuries, identifies key systemic deficiencies including the absence of PPE and safety training, and visualizes the widespread informal recycling of medical waste. The Fig. 4 emphasizes the heightened vulnerability of informal workers due to a lack of regulation, oversight, and institutional support. It may be observed from Fig. 4 that 62% of sanitation workers experienced injuries related to BMW handling, primarily needlestick incidents and infections. About 28% lacked access to personal protective equipment, while 10% remained unaware of health hazards linked with BMW exposure. Residential biomedical items such as syringes, soiled dressings, and expired pharmaceuticals frequently appeared mixed with general household waste, reflecting poor segregation. Informal activities involving manual sorting and unauthorized recycling of medical waste, such as repurposing discarded medicine strips and reusing contaminated protective gear,

Fig. 4: Health hazards and exposure pathways in informal BMW handling by waste workers

remained widespread, heightening pathogen exposure risk. Reported a 73% injury prevalence among Indian waste workers, with less than half consistently using protective equipment and few aware of post-exposure prophylaxis procedures. Sahai (2023) found that over 65% of informal waste handlers in urban slums experienced injuries or infections linked with unsegregated BMW, with only one-third accessing any safety training or protective gear. These earlier studies highlight occupational exposure and safety gaps. This study adds new dimensions by identifying specific high-risk behaviours such as unregulated recycling of contaminated materials and quantifying the combined burden of injury, lack of protection, and awareness shortfalls within the same workforce. Findings emphasize a neglected work environment, demanding structured safety training, reliable PPE availability, strict segregation enforcement at source, formal inclusion of informal workers within regulated frameworks, and strengthened oversight of handling practices.

Urban management challenges faced by ULBs

The study highlights critical regulatory gaps in the management of residential BMW across ULBs, revealing that 72% of ULBs lacked specific guidelines addressing residential BMW, which has led to widespread unregulated disposal practices. Table 5 presents the identified policy gaps and challenges in residential biomedical waste management within urban local bodies.

From Table 5, it could be noted that enforcement mechanisms are notably weak, with only 15% of cases involving penalties for improper disposal, indicating a lack of deterrence and accountability. Sarkar (2023) found that enforcement actions in Shimla and Solan remained limited, with just 18% of violations resulting in formal penalties, while overall compliance with segregation norms hovered below 40%. Furthermore, the BMW Management Rules (2016) explicitly exclude household waste, creating a legal vacuum that leaves residential waste outside the ambit of regulatory oversight. The only partial mandate for segregation is observed in Shimla, with other ULBs failing to enforce such critical practices, contributing to high levels of waste mixing and increasing the risk of environmental and public health hazards. The novelty of this finding lies in its focused identification of household-level regulatory blind spots within an otherwise structured BMW policy landscape. To address these issues, the study recommends amending the BMW Rules (2016) to include residential sources, introducing clear operational guidelines for ULBs, and implementing stringent enforcement with progressive penalties (Alzghoul *et al*., 2022). These actions are vital to closing policy gaps, enhancing compliance, and ensuring safe waste segregation and disposal at the household level. The inference drawn emphasizes that policy reform, backed by enforcement and public sensitization, is central to sustainable residential BMW management.

Table 5: Policy gaps in BMW management

Policy Aspect	Status in ULBs	Impact
Residential BMW rules	Absent (72%)	Unregulated disposal
Segregation mandates	Partial (Shimla only)	High mixing rates
Enforcement mechanisms	Weak (15% fines imposed)	Low compliance

Financial and infrastructural constraints

Fig. 5 represents the breakdown of key financial and infrastructural barriers. It could be noted from Fig. 5 that inadequate budget allocation emerges as the foremost challenge (30%), followed by lack of specialized equipment (25%), insufficient trained staff (20%), poor maintenance of infrastructure (15%), and limited access to technology (10%), all of which collectively hinder effective and sustainable waste management. This study uniquely quantifies these constraints, highlighting the significant impact of financial and resource deficiencies on waste management systems. In line with this, 80% of ULBs cited insufficient funds specifically for BMW collection. Only Shimla had a dedicated BMW treatment facility, while others relied on common incinerators. Collection frequency also varied significantly, with daily collection in Shimla compared to monthly in Bilaspur. Geographic and logistical barriers further complicate waste management in hilly cities. Transport costs are 30-40% higher in these areas, 40% of ULBs reported zones inaccessible during monsoons, and waste vehicles unsuitable for steep terrain in 55% of cases. These challenges disproportionately affect smaller ULBs, which struggle due to limited budgets and difficult terrain, while tourist influxes strain systems in Shimla and Dharamshala. Goswami *et al*., (2021) emphasize that during the COVID-19 pandemic, BMW volumes surged dramatically, exposing the vulnerabilities of existing infrastructure and resource constraints, thereby intensifying the need for enhanced budget allocations and capacity building. Sharma *et al*., (2023) highlight that adequate funding and technological investments are critical for circular economy initiatives and effective waste management, underscoring the global relevance of financial and infrastructural support. The findings imply that without sufficient funding and investment in technical and human resources, sustainable waste management remains difficult. Increasing budget allocations focused on equipment upgrades and staff capacity building, implementing regular infrastructure maintenance, and improving access to advanced technologies are essential. Addressing geographic and logistical barriers through tailored vehicle designs and improved transport strategies will also enhance operational efficiency, regulatory compliance, and overall system resilience.

ULB expenditure on waste management

ULBs allocate a significant portion of their municipal budgets to waste management; however, expenditure patterns reveal inefficiencies and imbalances. A large share of funds is often directed toward collection and transportation, while minimal investment is made in waste processing, segregation infrastructure, or public awareness campaigns. This skewed allocation limits the effectiveness of waste management systems and perpetuates reliance on landfilling and informal disposal practices. In many ULBs, there is no dedicated budget line for handling BMW, particularly from residential sources, reflecting its low priority in planning. The lack of financial provisioning for capacity building, monitoring, and enforcement further undermines the sustainability of waste management programs. Optimizing expenditure through targeted investments in segregation systems, decentralized processing units, and community engagement can significantly enhance operational outcomes and compliance with waste management regulations. Fig. 6 illustrates the percentage allocation of BMW management budgets across five urban centers: Shimla (62%), Solan (12%), Dharamshala (12%), Mandi (10%), and Bilaspur (8%), with an average benchmark of 13.4%. The results reveal significant disparities in municipal budget prioritization, with Shimla receiving disproportionately higher funding, while other cities remain under-resourced. This novel insight addresses previous research gaps that focused primarily on institutional frameworks without quantifying municipal investment disparities in BMW governance. Sarkar (2023) highlights similar challenges within urban governance in Indian hill states, emphasizing that

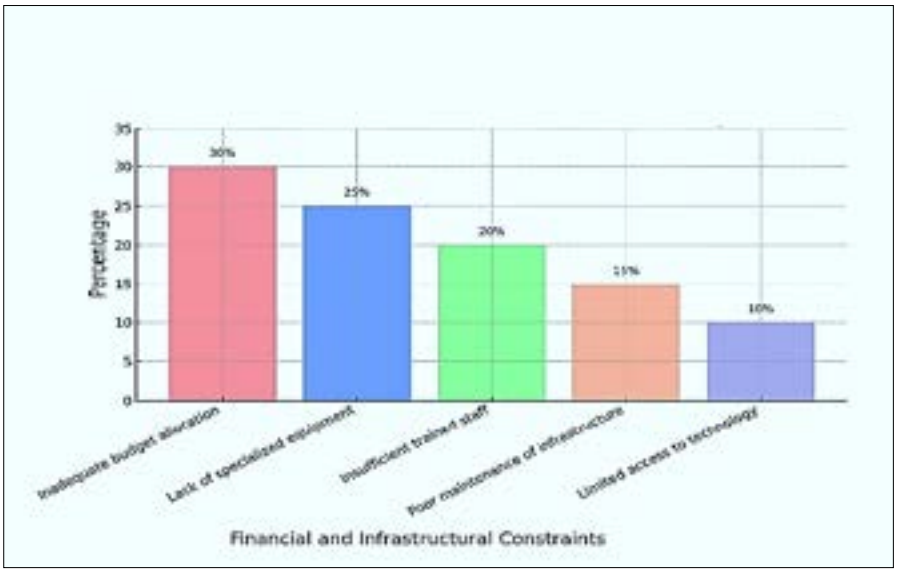

Fig. 5: Key financial and infrastructural barriers

Fig. 6: ULB expenditure on waste management

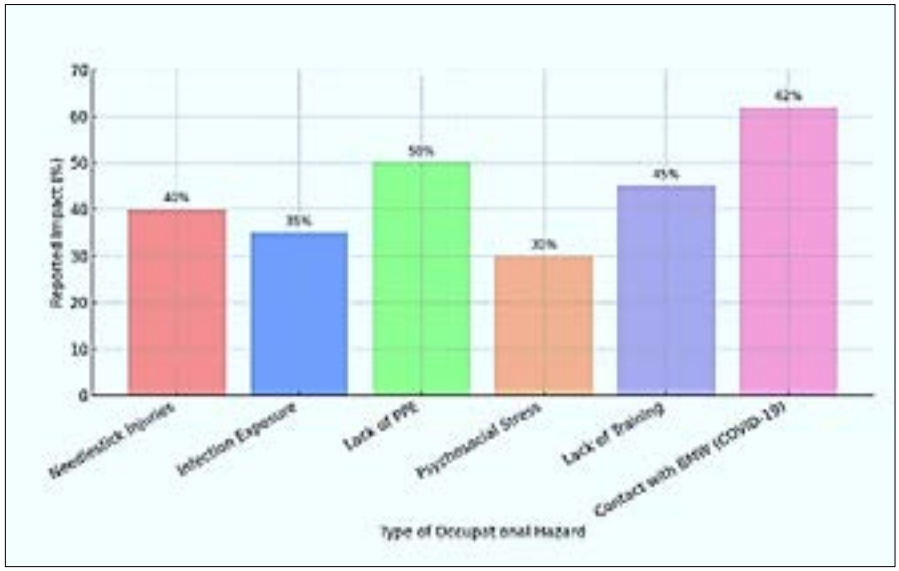

Fig. 7: Occupational hazards faced by sanitation workers in urban BMW management

unequal resource distribution undermines effective waste management, particularly in smaller ULBs such as Solan and Mandi. Goswami *et al*., (2021) note that the COVID-19 pandemic intensified the demand for robust BMW management infrastructure, revealing inadequacies in budgetary provisions and necessitating urgent policy reforms. Sharma *et al*., (2023) policy highlights reinforce the importance of equitable and data-driven budg*et al*locations to support circular economy principles and efficient waste management. The inference highlights systemic inequities, where financial constraints at the municipal level contribute to insufficient waste segregation, disposal inefficiencies, and heightened occupational risks for waste workers. Addressing these gaps necessitates policy interventions advocating equitable budg*et al*locations, structured financial planning, and standardized funding models across municipalities to optimize BMW management outcomes. Additionally, recommendations emphasize data-driven investment strategies integrating epidemiological trends and waste burden assessments to ensure proportional budget distribution aligned with urban BMW generation rates (Banal and Abad, 2025).

Public health risks in urban settings

Sanitation workers, including waste collectors, street sweepers, and ragpickers, form the frontline of BMW management in urban areas, yet they operate under hazardous and often overlooked conditions. In the absence of formal segregation systems, these workers are routinely exposed to improperly disposed biomedical materials such as used syringes, contaminated personal protective equipment (gloves, masks, gowns), sharps (needles, scalpels), and expired medications. This direct exposure significantly increases their risk of occupational injuries and infections. As shown in Fig. 7, sanitation workers face a range of occupational hazards, including needlestick injuries, infection exposure, lack of PPE, psychosocial stress, inadequate training, and frequent direct contact with BMW during emergencies like the COVID-19 lockdown. From Fig. 7, it may be noted that needlestick injuries are particularly common due to the frequent mishandling of mixed waste containing sharps, while prolonged contact with infectious waste elevates the likelihood of contracting serious diseases such as Hepatitis B and C, Human Immunodeficiency Virus (HIV), and various bacterial infections. Report that 58% of urban sanitation workers faced needlestick injuries, with 35% lacking access to adequate PPE, corroborating the high vulnerability of this workforce. A major concern is the lack of personal protective equipment, as many municipal workers report inadequate or irregular supply of essential items like gloves, boots, and face shields. Furthermore, most workers lack proper training in BMW handling procedures and risk mitigation strategies, leaving them ill-equipped to

protect themselves in dangerous environments. The WHO (2022) emphasizes that comprehensive training and consistent PPE provision reduce infection risks among healthcare and waste workers, underscoring a critical gap in current urban waste management practices. The psychological burden is equally concerning, as workers often face stigma, poor working conditions, and emotional stress, which contribute to low job satisfaction and mental health challenges. A critical finding from the study revealed that over 62% of surveyed workers in Shimla and Solan reported direct contact with suspected BMW mixed in household garbage during the COVID-19 lockdown phases, highlighting the urgent need for improved safety protocols, training, and institutional support for these essential yet vulnerable members of the urban waste management workforce.

Community exposure to infectious waste

Public health risks linked with BMW extend beyond occupational settings; they significantly affect community environments due to improper disposal practices. Unregulated dumping of infectious materials near residential areas has become a serious environmental and epidemiological concern. Many urban localities see households disposing of items such as used masks, blood-stained cotton swabs, insulin syringes, and expired medications into open municipal bins or roadside piles without segregation or containment. These materials often remain exposed for long periods, allowing direct human contact and environmental contamination. A particularly hazardous practice observed in several communities involves the open burning of BMW near residential dwellings. This releases harmful pollutants such as dioxins, furans, and particulate matter into the air, posing respiratory hazards and increasing long-term health risks, including carcinogenic effects. Samad *et al.,* (2019) documented significant groundwater contamination from BMW leachate in urban India, highlighting the extended environmental and public health implications of improper waste disposal practices. Additionally, informal scavenging involving children, rag pickers, and stray animals results in the handling and redistribution of infectious waste. These secondary transmission pathways increase the likelihood of disease spread within communities, especially in high-density or low-income settlements with limited access to healthcare and sanitation infrastructure. Sahai (2023) emphasizes that public health risks escalate sharply in urban slums due to unsegregated BMW mixing with MSW, exposing vulnerable populations to infectious agents and toxic substances. Scientific evidence shows that even low-level, chronic exposure to BMW through air, water, soil, or direct contact exacerbates public health vulnerabilities. Risks rise during health crises such as the COVID-19 pandemic when household BMW volumes increase substantially and conventional disposal systems become overwhelmed (Samadi Foroushani *et al*., 2024). Without systematic waste segregation, public awareness campaigns, and community-level safeguards, populations remain at heightened risk of exposure to pathogens and hazardous substances embedded within improper BMW management.

Health implications for communities

Burning BMWs releases tiny particulate matter along with highly toxic chemicals such as dioxins, which become suspended within the air, creating a hazardous environment for nearby residents. Continuous exposure can lead to respiratory problems, aggravate existing lung conditions, and increase vulnerability to lung infections. The pollution also contributes to the overall degradation of air quality, affecting community health beyond the immediate vicinity of burning sites. Leachate produced from open dumps carries harmful substances that seep through soil and reach local water bodies, posing severe threats to aquatic life and humans relying on these sources for drinking, cooking, or bathing. Pollutants can accumulate, causing disruptions to ecological balance and introducing pathogens capable of causing various diseases. Residents living near unmanaged dumps often experience higher rates of respiratory illnesses such as asthma and bronchitis, as pollutants released through waste degradation and open burning irritate respiratory tracts and compromise immune defenses. Vulnerable groups, including children, elderly individuals, and those with pre-existing conditions, suffer disproportionately. During pandemic situations, improper disposal of household items significantly worsens viral transmission, with contaminated items like used masks or tissues acting as fomites that enable disease spread through surface contact. When disposal systems become overwhelmed, infectious materials accumulate uncontained within communities, increasing the

chances of outbreaks and prolonging infection cycles. The WHO (2022) highlights that poor BMW management contributes to increased exposure to pathogens and environmental toxins, exacerbating community health burdens. Goswami *et al*., (2021) emphasize that the COVID-19 pandemic intensified BMW volumes, overwhelming existing systems and escalating public health hazards. These statistics underscore the direct health impacts of improper waste handling at the community level and highlight the urgent need for effective waste management practices, increased public awareness, and infrastructure improvements aimed at reducing exposure risks and promoting safer environments.

Case studies

Case study 1: Pilot interventions in Shimla and Solan ULBs

Addressing challenges related to residential BMW disposal and the resulting public health risks, two ULBs, Shimla and Solan, initiated pilot programs between 2022 and 2024 focused on sustainable waste management practices (Sharma and Acharya, 2019).

i. Objective: The intervention aimed at improving household-level BMW disposal through scheduled pickups, ensuring segregation at the source and safe handling during transport, thereby reducing exposure risks and supporting sustainable waste management.

ii Implementation: Electric vans fitted with dual compartments to separate infectious from general waste were introduced. These vehicles incorporated Global Positioning System (GPS) tracking and digital record-keeping to monitor participation across households disposing BMW. Municipal staff received specialized training and used PPE while collecting sealed BMW bags, ensuring worker safety and compliance with health protocols.

iii. Outcomes: The pilot engaged over 1,500 households in Shimla and more than 900 in Solan. Proper segregation compliance rose from 12% to 48% over six months, reflecting improved residential disposal practices. No needlestick injuries occurred among operators, highlighting enhanced safety measures.

iv. Challenges: Initial resistance stemmed from stigma and concerns about identification associated with BMW disposal at the household level. Operational difficulties emerged due to narrow streets and challenging hilly terrain, complicating consistent collection efforts and limiting scalability.

v. Positive highlight: Despite challenges, the mobile collection units significantly advanced safe BMW disposal, fostering better collaboration between urban authorities and residents. Regular engagement through scheduled pickups contributed to increased awareness and strengthened trust, supporting long-term sustainability goals.

Case study 2: Impact of the "3E (education, engineering, enforcement) strategy"

A holistic intervention known as the "3E Strategy" was launched alongside other initiatives, aiming at behavioural and systemic transformation related to residential BMW disposal (Ravindra *et al*., 2023).

i. Education: Community awareness drives utilized pamphlets, murals, local Frequency Modulation (FM) radio broadcasts, and school programs that engaged children as "waste ambassadors." Workshops conducted with Resident Welfare Associations (RWAs) further encouraged community participation and knowledge sharing.

ii. Engineering: Implementation included installation of dedicated BMW drop boxes within housing societies, introduction of color-coded household bins with yellow designated for BMW, and distribution of puncture-proof sharps containers specifically for diabetic patients.

iii. Enforcement: A penalty system addressed households repeatedly mixing BMWs, while compliant housing clusters received rewards. Monthly audits and inspections conducted by health officials ensured ongoing adherence and accountability without creating hostility among residents.

iv. Outcomes: The 3E Strategy yielded significant improvements across multiple metrics related to residential BMW management (Table 6). The percentage of households practicing proper segregation increased markedly from 11% before the intervention to 52% after, demonstrating nearly fivefold improvement in compliance. Complaints about mixed

Table 6: Impact measurement of the 3E strategy

Metric	Pre-intervention	Post-intervention
% of households with segregating BMW	11%	52%
Complaints about mixed waste	84/month	21/month
Reported waste worker injuries	19/quarter	2/quarter
BMW collected (kg/month)	120 kg	490 kg

waste disposal decreased sharply from 84 per month to 21 per month, indicating enhanced behavioural change and better adherence to segregation protocols. Reported injuries among waste workers declined dramatically, dropping from 19 injuries per quarter pre-intervention to only 2 per quarter post-intervention, reflecting the effectiveness of engineering controls such as puncture-proof sharps containers and enforcement of safe disposal practices. The total amount BMW collected increased substantially, from 120 kilograms (kgs) monthly before the strategy began to 490 kgs monthly afterward, suggesting improved reporting, collection efficiency, and community participation.

These results confirm that the 3E Strategy, combining education, engineering solutions, and enforcement measures, creates a synergistic effect, significantly improving residential BMW disposal practices. The approach enhances community ownership and accountability, strengthens institutional capacity, and supports sustainability without generating hostility. Positive changes observed within Shimla and Solan ULBs demonstrate the model's potential scalability and replication across similar urban settings facing public health and sustainability challenges associated with BMW.

The findings on residential BMW disposal practices in urban Himachal Pradesh can be theoretically understood through the lens of social practice theory and institutional governance frameworks. The widespread mixing of BMW with MSW (68% of households) reflects a systemic disconnect between waste management infrastructure and daily household practices. Social practice theory helps explain this phenomenon through its triad of materials, competences and meanings - where the absence of segregated bins (material dimension), lack of awareness about proper disposal (competence gap), and normalization of convenient mixing (social meaning) collectively sustain improper disposal behaviours. This situation mirrors Giddens' (1984) concept of the sequestration of risk, where households become unwitting risk producers while remaining detached from the consequences of their waste disposal choices. The hazardous conditions faced by informal waste pickers (89% encountering BMW daily, 62% reporting injuries) exemplify structural violence theory, revealing how urban waste systems systematically externalize risks onto marginalized labour forces. This creates a paradox where the very workers ensuring urban cleanliness bear disproportionate health burdens, reflecting neoliberal urban governance models that prioritize service delivery over worker protection. The urban management challenges faced by ULBs demonstrate critical gaps in institutional theory applications. The policy vacuum around residential BMW (absent in 72% of ULBs) reveals institutional isomorphism, where waste management systems mimic hospital-centric models without adapting to household contexts (Olusunmade, 2019). Financial constraints (reported by 80% of ULBs) align with resource dependency theory, showing how limited fiscal autonomy creates implementation bottlenecks. The geographic barriers in hilly terrain illustrate concepts from urban political ecology, where natural landscapes mediate urban service delivery through spatial mismatches and climate vulnerabilities. These interconnected challenges reflect multi-level governance failures, where disjointed policy frameworks, inadequate resource allocation, and geographical constraints collectively undermine waste management systems. The findings highlight a critical need for governance models that bridge institutional design with ground-level social practices, particularly in ecologically sensitive urban areas where conventional waste management approaches prove inadequate. This theoretical synthesis underscores the importance of developing context-specific frameworks that account for both the social production of waste behaviours and the institutional constraints shaping urban service delivery.

The results and discussion from this investigation into residential BMW disposal practices across urban centers in Himachal Pradesh reveal critical gaps in awareness, infrastructure, regulatory frameworks, and occupational safety that contribute to significant public health and environmental risks. Persistent mixing of hazardous BMW with general waste, inadequate enforcement of segregation norms, and insufficient budg*et al*locations exacerbates contamination and exposure, particularly in smaller ULBs with limited resources. Occupational hazards faced by sanitation workers, including frequent needlestick injuries, lack of personal protective equipment, and psychosocial stress, further highlight systemic neglect within waste management systems. Informal practices such as open burning and scavenging amplify community vulnerabilities, especially among marginalized populations. The study's integration of quantitative and qualitative data from household surveys, stakeholder interviews, and field observations provides novel insights into financial disparities, regulatory blind spots, and behavioural inconsistencies not fully addressed in prior research. These findings emphasize the urgent need for holistic, multi-level interventions encompassing policy reform, targeted public education, infrastructural investment, equitable budget distribution, and enhanced occupational health protocols to improve residential BMW management and mitigate associated risks.

Synthesis of findings and policy implications

This study systematically examined residential BMW management and associated urban governance challenges in Himachal Pradesh, revealing critical risks to public health and sanitation workers. Findings indicate that 68% of households mix BMW with general waste, primarily due to lack of awareness (42%), absence of dedicated bins (35%), and convenience (23%), with commonly discarded items including syringes, PPE, and expired medications. This unsafe disposal exposes communities to infectious waste and environmental contamination. Occupational hazards are substantial, as 89% of sanitation workers encounter BMW daily and 62% report injuries, including needle-stick incidents, while only 10% are aware of the hazards, and 28% lack proper PPE. Governance gaps exacerbate these risks: 72% of ULBs lack specific residential BMW guidelines, and only 15% enforce penalties, with financial and infrastructural constraints such as limited budgets, inadequately trained staff, and poor maintenance further hindering effective management. Improper disposal consequently contributes to increased respiratory and vector-borne diseases. The study also highlights successful pilot interventions, including mobile BMW collection units in Shimla and Solan and the "3E Strategy", which improved segregation compliance, reduced health risks, and enhanced community engagement, demonstrating scalable solutions for sustainable management. As one of the first studies to quantify residential BMW practices, occupational hazards, and governance gaps in this ecologically sensitive region, it provides evidence-based insights and emphasizes that integrated strategies combining policy reform, public awareness, infrastructure development, and occupational safety are essential for effective, sustainable biomedical waste management and public health protection.

Superiority of the present study

This study advances the existing body of knowledge on residential BMW management by providing a comprehensive, multi-city investigation across diverse urban centers in Himachal Pradesh, incorporating both household surveys (n=800) and stakeholder interviews (n=42). Unlike previous studies that predominantly focused on isolated aspects such as awareness or singular urban contexts (Samad *et al.,* 2019; Devi *et al.,* 2019), this research uniquely integrates behavioural, infrastructural, and regulatory dimensions to holistically assess inefficiencies in decentralized BMW disposal. The inclusion of field observations and municipal worker safety assessments further distinguishes this study, addressing critical gaps related to occupational hazards and informal waste handling practices, as highlighted by Sahai (2023). Moreover, the study provides empirical evidence on the inadequacies of current regulatory frameworks at the household level and quantifies budgetary disparities among ULBs, adding novel insights to governance challenges that were not explicitly quantified in prior research (Sarkar, 2023). This comprehensive approach underscores the complex interplay between behavioural, institutional, and infrastructural factors, thereby offering a robust foundation for targeted policy and operational reforms.

Challenges and limitations of the study

Despite providing valuable insights into residential biomedical waste management, the study has several limitations that should be considered when interpreting the findings.

1. *Limited geographic scope:* This study focuses on Himachal Pradesh, which may limit the generalizability of the findings; however, the insights are valuable for understanding residential BMW challenges in ecologically sensitive and hilly regions and can inform research in similar contexts.
2. *Exclusion of rural areas:* Although rural households were not included, the methodology and pilot interventions presented here can be adapted to rural settings to address similar or unique biomedical waste disposal challenges.
3. *Long-term evaluation of pilot interventions:* Pilot interventions were assessed over a limited period; however, initial results indicate improved waste segregation, reduced occupational hazards among sanitation workers, and enhanced community engagement, providing a basis for evaluating long-term sustainability and potential scalability.
4. *Short-term evaluation of pilot interventions:* While the pilot interventions were assessed over a limited period, initial results indicate improved waste segregation, reduced occupational hazards, and enhanced community engagement, providing a foundation for longer-term evaluation and potential scaling.
5. *Financial constraints:* Although the study does not provide detailed solutions for budgetary limitations, it emphasizes data-driven planning and scalable low-cost interventions, which can help smaller ULBs manage residential BMW more effectively.
6. *Limited stakeholder representation:* Although only 42 stakeholders were interviewed, the data provide valuable insights from municipal staff, informal waste workers, and policymakers; future studies could include broader stakeholder representation for more comprehensive perspectives.
7. *Absence of comparative analysis:* While this study does not compare Himachal Pradesh's practices with other Indian states or international models, it establishes a detailed baseline on residential BMW management, occupational hazards, and governance gaps that can inform future comparative studies.

Recommendations

To address the multidimensional challenges identified, several strategic actions are imperative:

i. *Policy reform and enforcement:* Amend the Biomedical Waste Management Rules (2016) to explicitly include residential sources, as 68% of households currently mix biomedical waste with general waste. Establish clear household-level segregation protocols and mandate accountability mechanisms for urban local bodies, 72% of which lack specific residential BMW guidelines and only 15% enforce penalties. Coupling policy amendments with progressive enforcement will help close regulatory gaps and institutionalize compliance.

ii. *Awareness and behavioural change:* Launch sustained public awareness campaigns to address the primary driver of improper disposal, with 42% of households citing lack of awareness and 23% convenience as reasons for unsafe practices. Community-based IEC initiatives and the "3E Strategy" (Education, Engineering, Enforcement) piloted in Shimla and Solan, which demonstrated measurable improvements in segregation compliance, should be scaled across smaller urban centers to normalize safe disposal behaviours.

iii. *Infrastructure development and investment:* Strengthen collection and treatment systems by addressing the absence of dedicated BMW bins in 35% of households and expanding mobile BMW collection units that have proven effective in pilot interventions. Investment in incinerators, autoclaves, and deep burial systems is needed to overcome financial and infrastructural constraints frequently reported by ULBs. Infrastructure planning must also consider region-specific challenges such as hilly terrains and seasonal tourist influx.

iv *Occupational safety enhancements:* Prioritize the protection of sanitation workers, 89% of whom encounter BMW daily and 62% of whom report injuries, primarily needle-stick incidents. Training programs, coupled with consistent provision of PPE currently lacking

for 28% of workers, should be institutionalized. Formal integration of informal waste handlers into regulated municipal systems can further reduce exposure risks and improve overall waste-handling efficiency.

v. *Data-driven governance and planning:* Improve decision-making by embedding data analytics into BMW management. GIS mapping, real-time monitoring, and waste audits can guide resource allocation, while epidemiological data on respiratory and vector-borne diseases linked to poor disposal practices can inform prioritization of interventions. Such evidence-based approaches will enhance operational efficiency, improve transparency, and strengthen the resilience of BMW systems in ecologically sensitive regions.

Future scope

Building upon the findings, future research should explore longitudinal studies to monitor behavioural and institutional changes following policy interventions, assessing their sustained impact on public health outcomes. Investigations into the efficacy of community-based decentralized BMW treatment technologies and their scalability in hilly terrains would provide practical insights. Additionally, socio-economic analyses of informal waste workers' integration into formal systems could inform socially inclusive waste governance models. Finally, expanding the geographic scope beyond Himachal Pradesh to other Indian hill states or similar settings internationally would enhance generalizability and foster comparative policy development.

CONCLUSIONS

This study provides a comprehensive examination of residential BMW disposal practices and the challenges faced by ULBs in Himachal Pradesh, India. Through a combination of household surveys, stakeholder interviews, and analytical mapping of urban waste flows, the study reveals critical gaps in waste segregation, infrastructure, and policy enforcement. Findings highlight that most urban households dispose of items such as syringes, expired medicines, and PPE along with general MSW, mainly due to a lack of awareness and inadequate systems for collection and disposal. ULBs face multilayered challenges, including outdated policy frameworks, insufficient technical capacity, and limited funding, all exacerbated by the geographic complexities of hilly terrains. The study also brings to light significant public health risks, with sanitation workers frequently exposed to infectious materials without proper protection, and communities facing secondary exposure through open dumps or incineration. Pilot interventions in Shimla and Solan, such as mobile BMW collection units and the "3E Strategy", demonstrated measurable success. These efforts improved waste segregation compliance, reduced health risks, and increased community engagement, offering a scalable model for sustainable urban BMW management. In conclusion, effective management of residential BMW in urban areas requires a multi-pronged approach: policy reform, targeted public education, infrastructure upgrades, and decentralized enforcement mechanisms. This research emphasizes the urgency of embedding BMW governance within broader public health and sustainability frameworks, especially in environmentally sensitive regions like Himachal Pradesh. The outcomes not only inform urban policymakers but also contribute to a resilient, inclusive waste management paradigm necessary for safeguarding human and environmental health in India's urban future.

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CONFLICT OF INTEREST

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

PUBLISHER NOTE

Tehran Urban Research & Planning Centre (TURPC) takes a neutral position on 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 (NOMENCLATURE)

BMW	Bio-Medical Waste
CPCB	Central Pollution Control Board
FM	Frequency Modulation
GIS	Geographic Information System
HIV	Human Immunodeficiency Virus
MSW	Municipal Solid Waste
MSW	*Municipal Solid Waste*
NGOs	Non-Government Organizations
PPE	Personal Protective Equipment
RWAs	Resident Welfare Associations
SBM	Swachh Bharat Mission
SDGs	Sustainable Development Goals
SWM	Solid Waste Management
SWOT	Strengths, Weaknesses, Opportunities, and Threats
ULB	Urban Local Body

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