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BIO-MEDICAL WASTE MANAGEMENT PERFORMANCE: A CROSS-SECTIONAL STUDY OF HEALTH CARE ESTABLISHMENTS IN DHAKA CITY, BANGLADESH

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Abstract: Effective bio-medical waste management (BMWM) is critical for urban public health; however, compliance across healthcare establishments (HCEs) are inconsistent and it remains a systematic challenge in Dhaka City Bangladesh. This study evaluated BMWM performance across diverse healthcare establishments (HCEs) using a weighted Bio-Medical Waste Management Performance Index (BMWMPI). A cross-sectional analysis of 177 HCEs was conducted across Dhaka North (DNCC), Dhaka South (DSCC), and peri-urban areas using an eight-pillar framework. Data were analyzed using Pearson correlation, One-way ANOVA with Tukey's HSD, and Random Forest regression to identify primary performance predictors. The overall BMWMPI averaged 5.287 (SD=1.236), reflecting moderate compliance. Private facilities (M=5.40) significantly outperformed government hospitals (M=4.45, p<0.01), and DNCC institutions scored higher than DSCC and peri-urban counterparts (p<0.01). While top-performing private HCEs demonstrated robust infrastructure, large public medical colleges exhibited critical operational deficiencies. Random Forest analysis identified a "safety–security–characterization" triad—comprising site security, waste characterization, and animal access—as the primary driver of performance. Results reveal a pervasive "structural-operational decoupling," where existing physical infrastructure is undermined by inadequate segregation and occupational safety protocols. Weak environmental containment and public exposure to waste elevate risks for healthcare workers and urban communities. Principal component analysis confirms that being a large facility does not generate superior protocols. Instead, multivariate modeling identifies PRISM Bangladesh involvement as the most powerful predictor of success, increasing livelihood of cleanliness standards by 13.9 times. Targeted regulatory enforcement and strengthened institutional accountability, particularly within public tertiary hospitals, are essential to enhance urban environmental governance and mitigate health risks. These findings highlight an urgent need for secured disposal zones, specialized waste staff, and public-private partnerships to bridge the compliance gap in high-volume facilities.

Key words: Bio-medical waste management; Segregation; Disposal; Performance index; Multivariate analysis; Random Forest, Urban Governance; institutional compliance and PRISM Bangladesh

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INTRODUCTION

Bio-medical waste management (BMWM) constitutes a fundamental component of healthcare service delivery, directly influencing public health protection, occupational safety, and environmental sustainability (Kannadhasan & Nagarajan, 2022). Healthcare establishments generate a complex mixture of hazardous and non-hazardous waste, including infectious materials, sharps, chemical residues, pharmaceuticals, and pathological waste, which require specialized handling, treatment, and disposal systems. Inadequate management of these waste streams increases the risk of needle-stick injuries, healthcare-associated infections, environmental contamination, and community exposure, particularly in densely populated urban settings (Akter, 2000; Akter & Tränkler, 2003; Thakur & Ramesh, 2015). Globally, approximately 20–25% of healthcare waste is considered hazardous, yet in many developing contexts it is frequently mixed with general waste and disposed of through informal or unsafe pathways (Alves et al., 2014; World Health Organization, 2011). Such practices expose healthcare workers, waste handlers, scavengers, and surrounding communities to injuries, infections, and long-term environmental contamination.

International research demonstrates that BMWM deficiencies are not geographically isolated but are systemic across diverse healthcare systems. Studies from Korea, Croatia, Turkey, Jordan, Myanmar, Nigeria, China, Cameroon, Greece, India and other settings document persistent challenges related to waste segregation, transportation, treatment, and final disposal, with incineration and landfilling remaining the dominant technologies despite their environmental trade-offs (Jang et al., 2006; Birpınar et al., 2009; Dzekashu et al., 2017; Patil & Pokhrel, 2005: Begum, et al 2021: Hamid et al. 2013). While these studies have substantially advanced understanding of waste composition and technical options, they often emphasize infrastructure or technology in isolation, offering limited insight into the operational, safety, and governance dimensions that ultimately determine real-world compliance.

The escalating volume of medical waste in urban centers like Dhaka represents a critical intersection of public health crisis and environmental degradation. Hospitals serve as the primary sources of hazardous waste generated during disease investigation, treatment, and research activities. The mismanagement of removal, collection, and disposal processes can lead to detrimental ecological effects and the spread of antibiotic-resistant pathogens (Rao et al., 2004). In a city like Dhaka, where nearly 90,000 kg of medical waste is generated daily and approximately 25% is highly infectious, the stakes for effective management are exceptionally high.

The relevance of BMWM is particularly acute in Bangladesh, where rapid urban growth, healthcare sector expansion, and constrained municipal capacity intersect. Dhaka City, one of the world's most densely populated megacities, has experienced an unplanned proliferation of public and private healthcare establishments, intensifying biomedical waste generation and environmental exposure risks. Medical waste in Bangladesh encompasses solid and liquid residues generated through diagnostic, therapeutic, preventive, and research activities in both human and veterinary contexts (Akter, 2000; Alam et al., 2013:

Hasan et al. 2008). Prior to the COVID-19 pandemic, hospitals in Bangladesh generated between 1.63 and 1.99 kg of waste per bed per day, a figure that increased sharply during the pandemic due to widespread use of personal protective equipment, diagnostic kits, and disposable medical supplies (Rahman et al., 2020; Ilyas et al., 2020). Pandemic-related waste alone increased from hundreds of tons per month in early 2020 to several thousand tons by 2021, placing unprecedented strain on already fragile waste management systems (Chowdhury et al., 2021).

Despite the existence of legal and policy frameworks, including the Medical Waste (Management and Processing) Rules of 2008, BMWM governance in Bangladesh remains weakly implemented. Institutional responsibilities among regulatory agencies and city corporations remain poorly delineated, and enforcement mechanisms are limited. Studies consistently report inadequate staff training, insufficient protective equipment, lack of segregation at source, and improper disposal into municipal waste streams (Sarker et al., 2014; Bhattacharjee & Saha, 2015; Ara et al., 2022). Evidence suggests that knowledge of BMWM among healthcare personnel is often insufficient, even in large hospitals, and that administrative oversight remains inconsistent across institutional types (Behnam et al., 2020). Most institutions continue to dispose of clinical waste in City Corporation bins, which is then transported to open municipal dumping sites. The World Health Organization (2011) highlights the gravity of this negligence, estimating that unsafe injections alone caused millions of Hepatitis B and C infections globally. In Dhaka, the operational reality is a complex mix of public-sector overburden and private-sector variability. While private hospitals often manage waste more hygienically due to lower patient volumes, the public sector struggles under the weight of massive demand and limited resources.

Accordingly, the overall objective of this study is to comprehensively evaluate bio-medical waste management performance across healthcare establishments in Dhaka City using a multidimensional index, and to determine how institutional characteristics, operational practices, environmental conditions, and geographic context collectively influence compliance, safety, and environmental risk. To achieve this objective, the study addresses the following research questions: (QI) What is the overall level of bio-medical waste management performance among healthcare establishments in Dhaka City? (QII) How does BMWM performance vary by healthcare establishment type, ownership, facility level, and geographic location? (QIII) Which waste management dimensions most significantly predict overall BMWM performance? (QIV) What relationships exist between waste disposal site characteristics, safety hazards, and environmental exposure risks? and (QV) To what extent do institutional, functional, and geographic factors explain variations in BMWM performance across urban healthcare facilities in Dhaka City?

MATERIAL AND METHODS

Study system: There are about 5816 small to large hospital and clinics in Dhaka City, out of them 337 are the government hospitals and remaining 5479 private hospitals and clinics. A total of 177 HCFs were selected randomly, of which 21 Government hospitals, 155 private owned hospitals and 1 NGO hospital. These study hospitals can be categorized on the basis of service type of which 114 general type, 18 medical college hospital and 45 specialized hospitals. These HCEs were the representative and widely distributed in the Dhaka City. In this study, existing waste management of few selected hospitals has been assessed to know the present handling, storage, transport, and treatment and disposal system of hospital wastes. This cross-sectional study was conducted to assess the existing medical waste management of hospital situating in Dhaka city. Among the selected hospitals, there were three private hospitals, one private medical college hospital and one government medical college hospital. Only those hospitals which are located in Dhaka city as well as have a waste management system were included in this study (Fig-1).

The study sites are widely distributed in the Dhaka North and South City Corporation. These Health Care Establishment (HCE) indiscriminately dump medical waste around their premises. High population density in the study sites assures that a large number of people are exposed to toxic level of medical waste. In addition, school children are considered to be most vulnerable because the study sites are mainly located close to schools. Almost all the HCE dispose their generated waste into the DCC bins located close to them.

Data Collection: This study was conducted from June to December 2025. It is a mixed-method study. Both qualitative and quantitative approaches were used in this paper. A structured questionnaire was designed to collect information addressing the generation of different medical wastes according to amount and sources from different HCE. A number of in-depth interviews were arranged to enhance our understanding of previous and existing management practice of medical wastes.

The questionnaire was designed following the objectives of this study. A total of 177 questionnaires were surveyed. The questionnaire mainly addressed the eight thematic pillars P1 (Status of Waste Disposal Sites), P2 (Biomedical Waste Characteristics), P3 (Site Security and Public Exposure), P4 (Animal and Bird Access), P5 (Infrastructure and Environmental Conditions), P6 (Food Vendors and Commercial Activities), P7 (Waste Management Practices), and P8 (Safety, Health, and other Observations). The occupation segmentation with gender heterogeneity was considered to select our respondents. All of the female respondents were nurses, and the rest were doctors, medical technicians, and cleaners. Apart from the formal questionnaire survey, we had informal discussions with patients for their understanding about existing medical waste management.The waste generation rates in the surveyed HCE were obtained by actual measurements and through assessment of the storage facilities emptying frequencies and the degree of filling of the refuse receptacles. Different wastes were used to store in different sizes of buckets in different wards, and surgery departments. The weight of these wastes was then measured in kilograms. The quantity of waste in different categories was collected twice in a day when the refuse receptacles emptied, but, in surgery departments, nurses provided us additional information regarding the quantity of generated wastes. We were very

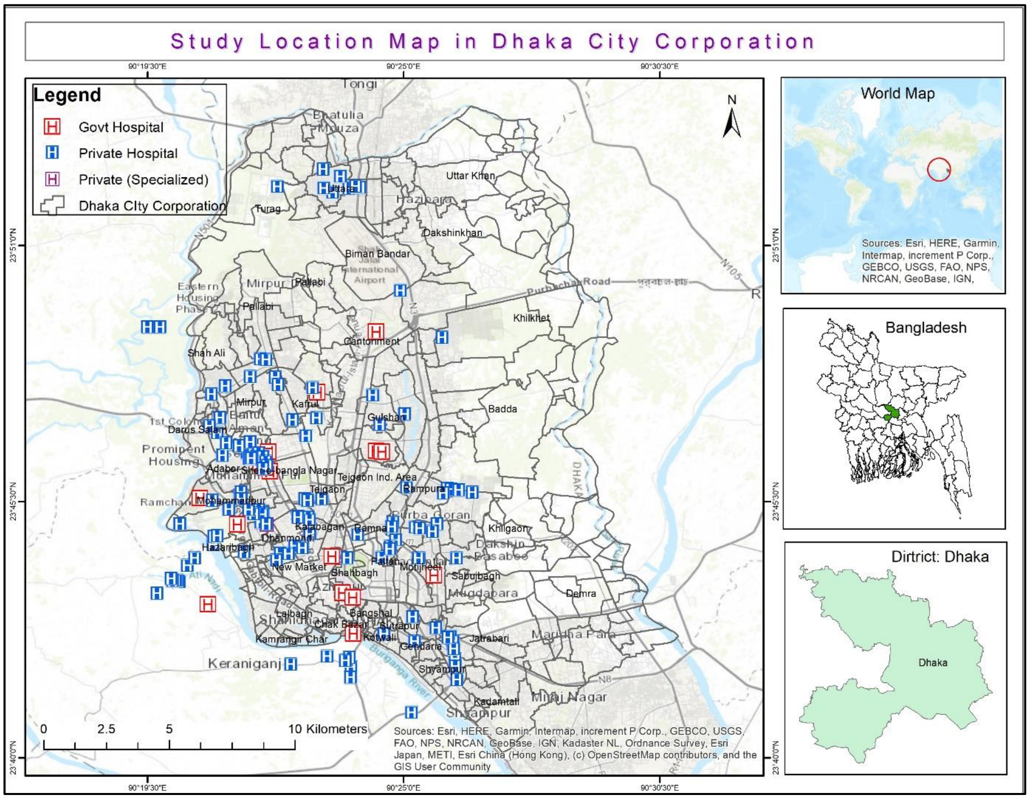

Fig.1. Study location map in Dhaka city corporation

careful about our data and nurses were helpful in gathering the relevant information. The WHO guidelines were followed to categorize the generated wastes from different HCE in the study sites.

Data analysis

Descriptive Statistics: The data has been analyzed in long format, linking each statement of unique respondents. Data imported from CSV files were cleaned. Descriptive analyses were conducted to summarize facility characteristics and BMWM conditions. Frequencies, percentages, means, medians, standard deviations, and interquartile ranges were calculated as appropriate to describe distributions and central tendencies. Descripting summary of BMWM PI is given in the Table-1.

Multi-Criteria Decision Analysis (MCDA): The observational data were analyzed using a structured scoring framework to develop a composite Bio-medical Waste Management Performance Index (BMWMPI). Qualitative field observations were transformed into quantifiable metrics using a custom mapping algorithm that recoded categorical responses into a numeric scale from 0 to 10, where 10 represents optimal compliance or minimal environmental risk and 0 represents high-risk conditions.

Table 1. Descriptive summary of BMWMPI

Parameter	n	Mean	Median	SD	IQR	Min	Max
P1: Disposal Site	177	6.322	6.333	1.188	1.917	4.333	9.5
P2: Waste Char.	177	2.456	1.667	2.987	3.333	0	10
P3: Security	177	6.006	6.667	3.38	6.333	0	10
P4: Animal Access	177	4.966	4.333	3.033	6	0	9.333
P5: Environment	177	7.964	8.25	1.444	2.5	5	10
P6: Commercial	177	2.979	3.75	1.385	2.5	1.25	6.25
P7: Practices	177	6.977	8	2.369	5	0	10
P8: Safety	177	4.626	3.333	2.838	4.667	0	10
Final Weighted Index	177	5.287	5.01	1.236	1.448	2.688	8.667

This multidimensional index was constructed around eight thematic pillars (management dimensions) designed to capture the complexity of the waste management: The mathematical construction of the index followed a Multi-Criteria Decision Analysis (MCDA) framework (Manga et al., 2011). Each pillar score (P_k) was calculated as the arithmetic mean of its constituent indicators. For pillars involving binary observations, such as the presence of specific waste items or the availability of color-coded containers, a nested row-wise mean was applied to capture the density of compliance. The final BMWMPI for each healthcare facility was derived by averaging the eight distinct pillar scores, ensuring that each thematic domain contributed equally to the final performance metric. The final index was calculated as:

$$\text{BMWMPI} = \frac{1}{n}\sum_{n=1}^{\infty} p_i$$

Where n = 8 and p_i represents the normalized score of the i^{th} pillar.

Inferential Statistics: Pearson correlation coefficients were computed to examine relationships among the eight BMWM pillars, particularly between environmental, safety, and management dimensions (Pearson, 1895). To compare BMWMPI scores across geographic locations, ownership types, facility levels, and institutional categories, one-way Analysis of Variance (ANOVA) was performed (Fisher, 1925). Where statistically significant differences were identified, Tukey's Honestly Significant Difference (HSD) post-hoc tests were applied to determine pairwise group differences (Tukey, 1949). A significance level of $p < 0.05$ was used throughout.

Predictive Modeling: Variable importance was assessed using Percent Increase in Mean Squared Error (%IncMSE) and Increase in Node Purity, allowing identification of the most critical predictors contributing to BMWMPI variation. This machine-learning approach was selected to capture complex, non-linear relationships among BMWM dimensions that may not be adequately represented in traditional regression models. Data analysis was conducted using R Statistical Software (version 4.5) including different packages such as tidyverse v2.0 (Wickham et al., 2019), ggplot2 v4.0.1 (Wickham, 2016)., janitor v2.2.1, broom v1.0.11 GGally v2.4.0 (Schloerke B. et al., 2025). viridis v0.6.5, Hmisc v5.2-5 (Harrell, 2025), ggpurb v0.6.2, random Forest v4.7-1.2 (Liaw & Wiener, 2025), brant v0.3-0 (Thomas et al., 2025)

RESULTS AND DISCUSSION

Descriptive summary: Healthcare facilities/hospitals were primarily concentrated within Dhaka City Corporation, with 53.7% located in Dhaka North City Corporation and 28.8% in Dhaka South City Corporation; 17.5% were situated outside City Corporation areas. Private ownership predominated, accounting for 87.6% of facilities, while government hospitals comprised 11.9% and NGO-operated facilities 0.6%. General hospitals represented 64.4% of the facilities, followed by specialized hospitals (25.4%) and medical college hospitals (10.2%). Combined, general and medical college hospitals constituted 74.6% of all facilities. Among specialized hospitals, mother and child care hospitals (6.8%) and eye hospitals (5.1%) were the most common, with other specialties present in smaller proportions. Most facilities were tertiary-level institutions (73.4%), with secondary- and primary-level facilities accounting for 15.8% and 10.7%, respectively. Large facilities comprised 74.6% of the sample, while medium and small facilities represented 23.2% and 2.3%, respectively Most healthcare facilities (73.4%) maintained waste disposal sites within hospital premises, with 78.5% of these sites located within 0–50 meters of the main entrance. Regarding site structure, 37.3% of disposal areas were properly closed, while 61.6% were either open or partially open. In terms of accessibility, 52.0% of sites were accessible to humans, whereas 41.8% had restricted access. At the point of disposal, proper waste segregation was observed in 16.9% of sites, while 37.9% showed no segregation. The remaining sites exhibited partial segregation or indeterminate segregation status, indicating that the majority of disposal sites involved mixed waste handling (Table-2). Biomedical waste was visibly present at 86.4% of the surveyed sites. The most frequently observed waste types were bandages and gauze (83.6%), syringes and needles (83.6%), medicine containers (81.9%), and partially used vaccines (72.3%). General waste, including food remnants, office waste, and packaging materials, was found mixed with hazardous biomedical waste at 84.2% of sites. Color-coded waste containers were available in 68.9% of facilities. Proper sharps disposal practices were observed in 65.5% of facilities, while 34.5% did not follow appropriate sharps

Table 2. Status of Waste Disposal Sites

Description	Category	N=177	Percentage
Location of waste disposal site	Both inside and outside	22	12.4
	Other	3	1.7
	Outside hospital premises	22	12.4
	Within hospital premises	130	73.4
Other waste disposal location (specified)	Basement	1	0.6
	None observed	2	1.1
Distance from hospital main entrance	0-50 m	139	78.5
	101-200 m	7	4
	51-100 m	24	13.6
	> 200 m	7	4
Description of waste disposal site	Closed	66	37.3
	Mixed	46	26
	Open	63	35.6
	Other	2	1.1
Condition of disposal site	Easy Access to humans	92	52
	Easy Access to stray animal	1	0.6
	Easy access to birds	1	0.6
	Restricted for birds	6	3.4
	Restricted for humans	74	41.8
	Restricted for stray animal	3	1.7
Waste segregation practice at disposal site	Cannot determined	33	18.6
	No segregation	67	37.9
	Partial Segregation	47	26.6
	Proper segregation visible	30	16.9

disposal procedures. Environmental conditions around disposal areas indicated that 72.3% of sites reported a bad or moderate odor. In addition, 66.1% of waste areas were dry, whereas the remaining sites exhibited moist or muddy conditions (Table-3)

Table 3. Biomedical Waste Characteristics

Description	Category	N=177	Percentage
Biomedical waste visible	Not visible	24	13.6
	Visible	153	86.4
Types of biomedical waste observed	Bandages and gauze	148	83.6
	Expired vaccine or drug	108	61
	IV bags/tubes	113	63.8
	Laboratory samples/containers	127	71.8
	Medicine bottles/containers	145	81.9
	Partially-used vaccine	128	72.3
	Pharmaceutical waste	127	71.8
	Syringes and needles	148	83.6
General waste mixed with biomedical waste	Yes	149	84.2
	No	28	15.8
Types of general waste mixed with biomedical waste	Food waste	149	84.2
	Office waste	147	83.1
	Packaging materials	149	84.2
	Plastic bottles	149	84.2
Color-coded waste containers observed	Yes	122	68.9
	No	55	31.1
Types of color-coded waste containers	Black containers	76	42.9
	Green containers	102	57.6

Description	Category	N=177	Percentage
	No color coding observed	2	1.1
	Red containers	120	67.8
	Yellow containers	117	66.1
Sharps materials disposal practice	Yes	116	65.5
	No	61	34.5
Smell around waste area	Bad	52	29.4
	Moderate	76	42.9
	No Smell	49	27.7
Wetness of waste area	Dry	117	66.1
	Moist	56	31.6
	Muddy	4	2.3

Most facilities (66.1%) reported no public access to waste areas; however, 58.2% of sites were observed to have accessible waste areas. Unrestricted public access was identified at 19.2% of facilities. Complete fencing of waste areas was present at 41.8% of sites, while 39.0% were partially fenced and 19.2% had no fencing. Evidence of waste scavenging was not observed at 84.7% of sites; however, active scavenging was recorded at 7.9% of sites, and signs of recent scavenging were identified at 6.8%. Specific security measures to prevent scavenging were reported by 0.6% of facilities (Table-4).

Table 4 . Site Security and Public Exposure to waste

Description	Category	N=177	Percentage
Access to waste area	No	74	41.8
	Yes	103	58.2
Barrier/fencing around waste area	Completely fenced	74	41.8
	No barriers	34	19.2
	Partially fenced	69	39
Public access level to waste area	Limited access	25	14.1
	No public access	117	66.1
	Unrestricted access	35	19.8
Presence of waste scavengers	Evidence of recent activities	12	6.8
	No evidence of scavenging	150	84.7
	Present during observation	14	7.9
	Security measures against scavenging	1	0.6

Animal and bird infiltration at waste disposal sites point toward a significant failure in environmental containment. Easy access for animals to waste disposal sites was observed at 52.0% of facilities, while only 7.3% of sites were classified as well protected. Waste scattering by animals or birds was recorded at 58.8% of sites. Among animals observed at disposal areas, cats were most common (54.2%), followed by dogs and, less frequently, cattle. Bird presence was not

Table 5. Animal and Bird Access to the waste disposal areas

Description	Category	N=177	Percentage
Animal access to waste area	Easy access for animals	92	52
	No animal presence observed	57	32.2
	Partially restricted	15	8.5
	Well-protected from animals	13	7.3
Types of stray animals	Cat	96	54.2

Description	Category	N=177	Percentage
observed	Cattle	1	0.6
	Dog	7	4
	None	73	41.2
Types of birds observed	Crows	63	35.6
	Kites	2	1.1
	No observation	98	55.4
	Pigeons	8	4.5
	Sparrows	6	3.4
Other bird species observed	None observed	166	93.8
	Martin	3	1.7
	Pigeons	8	4.5
Waste scattered by animals or birds	No	73	41.2
	Yes	104	58.8

observed at 55.4% of sites; however, crows were recorded at 35.6% of facilities, with pigeons and sparrows observed in smaller proportions (Table-5).

Drainage systems were present at 92.7% of hospital, of which 93.2% were functional. Covered functional drains accounted for 55.4% of the systems. Medical waste was not observed in drains at 63.8% of sites. Evidence of waste mixing with nearby water bodies was identified at 54.8% of facilities, including rivers (17.5%), ponds (13.6%), and lakes (5.1%). In addition, waste mixing with

Table 6. Infrastructure and Environmental Conditions at the Waste Disposal Site

Description	Category	N=177	Percentage
Drainage system around hospital	No	13	7.3
	Yes	164	92.7
Type of drainage system	Functional drain	165	93.2
	No drain	6	3.4
	Other	3	1.7
	Stagnant drain	3	1.7
Other drainage system specified	Covered drain	28	15.8
	Covered functional drain	98	55.4
	Half covered drain	1	0.6
	Half covered functional drain	1	0.6
	Open functional drain	1	0.6
Density of medical waste disposed into drains	Cannot access	17	9.6
	High	3	1.7
	Low	18	10.2
	Moderate	26	14.7
	None observed	113	63.8
Presence of nearby water bodies	Lake	9	5.1
	Other	113	63.8
	Pond	24	13.6
	River	31	17.5
Other water bodies observed	Active cannel	3	1.7
	Covered functional drain	11	6.2
	Functional drain	59	33.3
	Not mentioned	74	41.8
Waste mixed in water bodies	No	80	45.2
	Yes	97	54.8
Waste mixed in lowland /	No	116	65.5

Description	Category	N=177	Percentage
agricultural land	Yes	61	34.5
Waste collection vehicle access	Difficult access	5	2.8
	Easy access for collection vehicles	163	92.1
	No vehicles access	7	4
	Waste collection vehicle observed	2	1.1
Type of waste collection vehicle	Cannot determine	3	1.7
	Designated vehicle	84	47.5
	General vehicle	18	10.2
	Manual collection	36	20.3
	No vehicle observed or reported	36	20.3

lowland or agricultural land was reported at 34.5% of sites. Easy access for waste collection vehicles was available at 92.1% of facilities. Designated waste collection vehicles were used by 47.5% of facilities, while 30.5% relied on manual collection or general-purpose vehicles (Table-6). Vendors were present within hospital premises at 89.3% of facilities, with stationary food and fruit sellers observed at 82.5% of sites. Additional on-site services, including tea stalls, pharmacies, and mobile financial services, were present at 85.9% of facilities. Commercial activities within a 100-meter radius of healthcare facilities were reported at all sites (100%), including hotels and restaurants (98.9%), pharmacies (98.9%), general markets (96%), residential areas (96%), and other healthcare facilities (83.1%). Food preparation in close proximity to waste disposal areas was observed at 39.0% of establishments, while 60.5% of sites showed no visible cross-contamination (Table-7).

Table 7. Food Vendors and Commercial Activities in the study areas

Description	Category	N=177	Percentage
Presence of vendors within hospital premises	No	19	10.7
	Yes	158	89.3
Type of vendors	Canteen	2	1.1
	Mobile food/fruit seller	11	6.2
	Other	1	0.6
	Stationary food/fruit seller	146	82.5
Other types of vendors specified	Bkash shop, atm booth	6	3.4
	None observed	19	10.7
	Tea, canteen, medicine & MPO	152	85.9
Commercial activities within 100 m of hospital premises	Yes	177	100
Types of commercial / adjacent activities observed	Diagnostic centers	129	72.9
	Hotels / restaurants	175	98.9
	Market / commercial areas	170	96
	Other healthcare facilities	147	83.1
	Pharmacies	175	98.9
	Playing grounds	23	13
	Residential areas	170	96
Potential cross-contamination risk	Food preparation near waste	69	39
	No cross-contamination observed	107	60.5
	Waste affecting commercial areas	1	0.6

Daily waste collection was reported at 66.7% of healthcare facilities, while 27.1% had no regular collection system. Dedicated medical waste vehicles were used by 64.4% of establishments, with 21.5% relying on general-purpose vehicles and 14.1% using manual collection. Cleaning staff and workers handled waste disposal at 85.9% of sites, with City Corporation cleaners involved at 72.9% of facilities and private waste contractors engaged at 23.2% of sites (Table-8). Safety hazards reveal a critical risk to healthcare workers and the public. Exposed sharp objects were observed at 71.2% of waste disposal sites. Chemical hazards were noted at 5.1% of sites, and 23.7% of areas were free of immediate safety risks. Use of full Personal Protective Equipment (PPE) by waste handlers was observed at 1.1% of sites, while 27.7% showed no PPE usage. Rainwater accessibility affected 54.2% of disposal areas. Visible community health

Table 8. Waste Management Practices in the disposal areas

Description	Category	N=177	Percentage
Waste collection frequency	Daily collection	118	66.7
	Every 2-3 days	8	4.5
	No regular collection	48	27.1
	Weekly collection	3	1.7
Waste transportation method	Dedicated medical waste vehicle	114	64.4
	General waste collection vehicle	38	21.5
	Manual waste collection	25	14.1
Person responsible for disposing waste into hospital bins	Cleaning staff/workers	152	85.9
	Ward attendants	25	14.1
	City corporation cleaner	129	72.9
	Outsourced waste collection personnel	7	4
	Privet waste collection company	41	23.2

concerns were reported at 12.4% of sites. Hospital surroundings were rated as clean at 55.9% of facilities and moderately clean at 38.4%. Waste bins were present at 74.0% of hospital entrances (Table-9).

Table 9. Safety, Health Concerns, and Other Observations from the study areas

Description	Category	N=177	Percentage
Safety hazards observed	Chemical exposed	9	5.1
	No immediate safety hazard	42	23.7
	Sharp objects exposed	126	71.2
Use of personal protective	No PPE observed	49	27.7
	No waste handlers present	121	68.4
	Partial PPE usage	5	2.8
	Waste handlers using PPE	2	1.1
Perceived community health impact	Cannot access	69	39
	No apparent health issue	80	45.2
	Residents complaining	6	3.4
	Visible health concern	22	12.4
General cleanliness of hospital environment	Hospital surrounding clean	99	55.9
	Moderately clean	68	38.4
	Poor cleanliness	8	4.5
	Very poor cleanliness	2	1.1
Presence of waste bins at hospital entrance	No	46	26
	Yes	131	74
	No	55	31.1
	Yes	122	68.9
Access of rainwater to waste disposal area	No	81	45.8
	Yes	96	54.2

Bio-Medical Waste Management Performance Index: Bio-Medical Waste Management (BMWM) Performance Index across N = 177 Health Care Establishments (HCEs) reveals significant variability in compliance across the eight evaluated management dimensions. The Final Weighted Index yielded a mean score of 5.287 (SD = 1.236) and a median of 5.01, indicating that the overall performance of the sampled HCEs around a moderate compliance threshold. The relatively narrow Interquartile Range (IQR = 1.448) suggests that while extreme outliers exist (ranging from a minimum of 2.69 to a maximum of 8.667), the majority of facilities demonstrate a consolidated but mediocre performance profile. An evaluation of the individual pillars reveals a stark contrast between structural capacity and operational execution. P5 emerged as the most robust dimension (M = 7.964, Mdn = 8.25), with its low standard deviation (SD = 1.444) indicating a consistent baseline of physical adequacy across the sampled HCEs. In contrast, significant operational failures were observed in (P2) (M = 2.456, Mdn = 1.667) and (P6) (M = 2.98), where high positive skewness and substantial dispersion (SD, P2 = 2.99) suggest that a majority of facilities fail to meet even basic waste characterization standards, with the mean being inflated by a small subset of high-performing outliers.

Critical gaps also persist in P8, where the median (3.333) falls markedly below the mean (4.626), confirming that the typical institution operates under substandard safety conditions. Furthermore, the high interquartile ranges for Site Security (P3, IQR = 6.333) and Animal Access (P4, IQR = 6.0) underscore a profound lack of standardization, reflecting extreme institutional inconsistency in managing external environmental threats and security protocols (Figure-3).

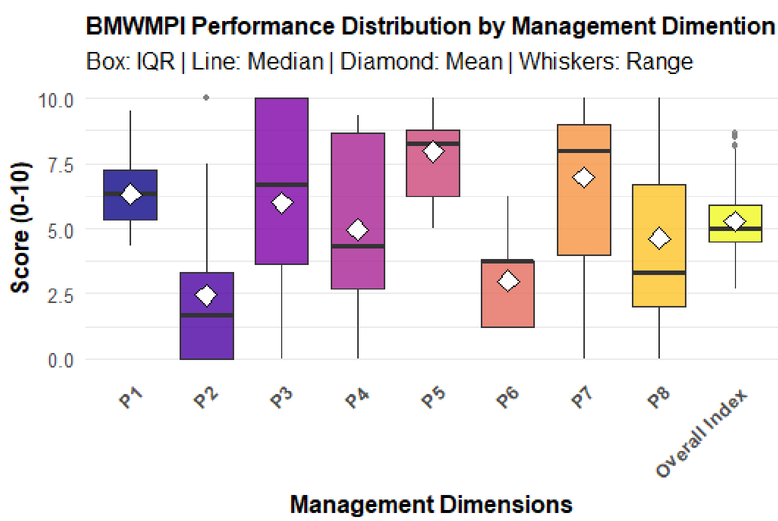

Fig.3: BMWM PI performance distribution by management dimension

Top- performing health care establishments: The highest-ranking facilities were predominantly private-sector hospitals. Alok Hospital Ltd. (Main Branch) achieved the highest performance index (M = 8.67, Rank 1), followed closely by

OGSB Hospital & Institute of Reproductive & Child Health (M = 8.54, Rank 2). Anwar Khan Modern Hospital (M = 8.51, Rank 3). HCEs in the top decile demonstrated high compliance across all eight pillars, specifically in infrastructure and standardized segregation protocols. Notably, several institutions shared rankings due to identical weighted scores, such as BRB Hospitals Ltd. and Mirpur Holy Crescent Hospital (Pvt.) Ltd., both ranking 9th with an index of 8.01 (Fig.-4).

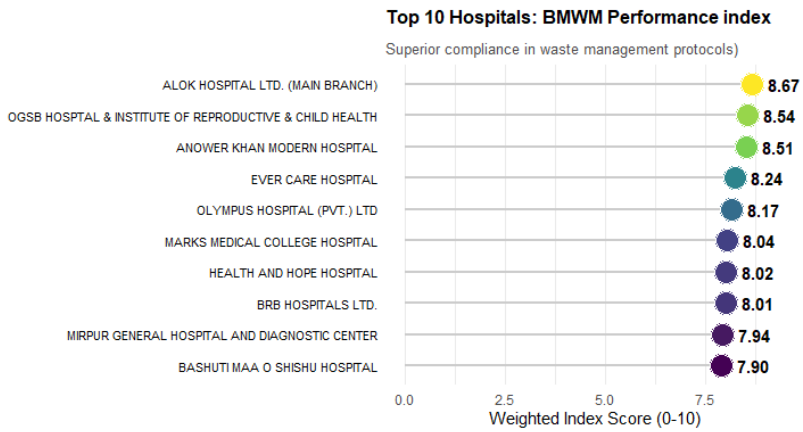

Fig.4: Top 10 HCEs by BMWM performance index

Least-performing health care establishments: Conversely, the lower end of the performance spectrum was characterized by large-scale public medical colleges and specialized national institutes. The National Institute of Cancer Research & Hospital recorded the lowest performance index (M = 2.69, Rank 140). Other major public institutions, including Dhaka Medical College Hospital (M = 3.05, Rank 139) and Mugda Medical College Hospital (M = 3.07, Rank 138), also featured among the least-performing HCEs. This indicates a significant performance gap between specialized private facilities and high-volume public hospitals, where the scale of waste generation may exceed current institutional management capacity (Fig.-5).

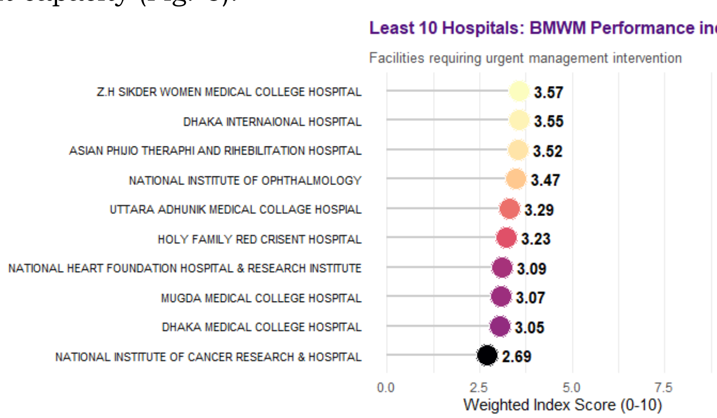

Fig.-5: Least 10 HCEs by BMWM performance index

Correlation among the management dimension of the BMWM PI: Pearson correlation coefficients were calculated to examine the relationships between waste disposal site characteristics and safety outcomes Table 10. Table Analysis ANOVA table analysis has been done by BMWM PI Table 11. & BWMPI_PostHoc_Turkey_Results is given in the Table 12. The analysis revealed a strong, statistically significant positive correlation between (P4) and (P8) ($r = 0.699$, $p < .001$), suggesting that faunal intrusion is a primary indicator of degraded safety conditions. Furthermore, Safety and Health (P8) were significantly associated with Food Vendors and Commercial Activities (P6) ($r = 0.364$, $p < .001$) and Biomedical Waste Characteristics (P2) ($r = 0.360$, $p < .001$), highlighting the multi-dimensional nature of site hazards. Conversely, (P7) demonstrated significant negative correlations with Animal/Bird Access ($r = -0.264$, $p < .001$) and Safety/Health Hazards ($r = -0.282$, $p < .001$). This inverse relationship indicates that standardized management protocols are effective in mitigating environmental risks. Additionally, Infrastructure (P5) was moderately linked to both animal intrusion ($r = 0.347$) and health observations ($r = 0.316$), underscoring the role of physical site conditions in maintaining overall disposal site integrity.

Table 10. Correlation Table

	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**
P1	-	0.280***	0.367***	0.088	0.084	0.086	-0.113	0.166*
P2	0.280***	-	0.282***	0.257***	0.285***	0.072	-0.129	0.360***
P3	0.367***	0.282***	-	0.032	0.185*	0.046	0.281***	0.032
P4	0.088	0.257***	0.032	-	0.347***	0.356***	-0.264***	0.699***
P5	0.084	0.285***	0.185*	0.347***	-	0.198**	0.097	0.316***
P6	0.086	0.072	0.046	0.356***	0.198**	-	-0.086	0.364***
P7	-0.113	-0.129	0.281***	-0.264***	0.097	-0.086	-	-0.282***
P8	0.166*	0.360***	0.032	0.699***	0.316***	0.364***	-0.282***	-

Table 11. ANOVA by BMWMPI

Category	**Group**	**N**	**Mean**	**SD**	**Test**	**P_Value**
City corporation/ Location	DNCC	95	5.58	1.35	Anova	0.002
	DSCC	51	5.01	1.2		
	Outside from CC	31	4.84	0.51		
HCEs Type	Government Hospital	21	4.45	0.97		0.004
	NGO Hospital	1	5.02	NA		
	Privet Hospital	155	5.4	1.23		
Facility level	Primary	19	4.33	0.49		<0.001
	Secondary	28	5.05	0.9		
	Tertiary	130	5.48	1.3		
Facility Size	Large	132	5.19	1.19		0.211
	Medium	41	5.58	1.39		
	Small	4	5.37	0.63		

The influence geographical disparities, institutional, and functional factors on BMWM PI: The operational and demographic profiles of the sampled healthcare establishments ($N = 177$) reveals that geographic location, institutional ownership, and facility level are significant determinants of waste management performance. Facilities within the Dhaka North City Corporation (DNCC)

Table 12. BWMPI_PostHoc_Tukey_Results

Category	Comparison	Difference	Lower_CI	Upper_CI	P_Adj
City Corporation	DSCC-DNCC	-0.5665	-1.059	-0.074	0.0196
	Outside from CC-DNCC	-0.7399	-1.3267	-0.153	0.0092
	Outside from CC-DSCC	-0.1734	-0.8196	0.4727	0.8014
Facility Level	Secondary-Primary	0.7207	-0.1134	1.5548	0.1052
	Tertiary-Primary	1.1458	0.4566	1.8351	4.00E-04
	Tertiary-Secondary	0.4251	-0.1596	1.0098	0.2011
Facility Size	Medium-Large	0.389	-0.1316	0.9097	0.1841
	Small-Large	0.1735	-1.3044	1.6515	0.9584
	Small-Medium	-0.2155	-1.7409	1.3099	0.9404

demonstrated significantly higher compliance (M = 5.58, SD = 1.35) compared to those in the Dhaka South City Corporation (DSCC) and peri-urban areas ($p = 0.002$), suggesting a spatial disparity in regulatory oversight or infrastructural support. Institutional ownership further influenced outcomes, as Private Hospitals (M = 5.40) significantly outperformed Government Hospitals (M = 4.45, $p = 0.004$), highlighting a critical performance gap in the public sector (Figure-6). Moreover, a strong positive gradient was observed regarding Facility Level ($p < 0.001$), with Tertiary-level institutions achieving the highest mean scores (M = 5.48), indicating that advanced institutional capacity and resource availability are essential for effective protocol implementation. Notably, Facility Size did not emerge as a statistically significant predictor of BMWMPI ($p = 0.211$), implying that the functional tier and management type of a facility are more influential than its physical scale or patient capacity (Fig.-6).

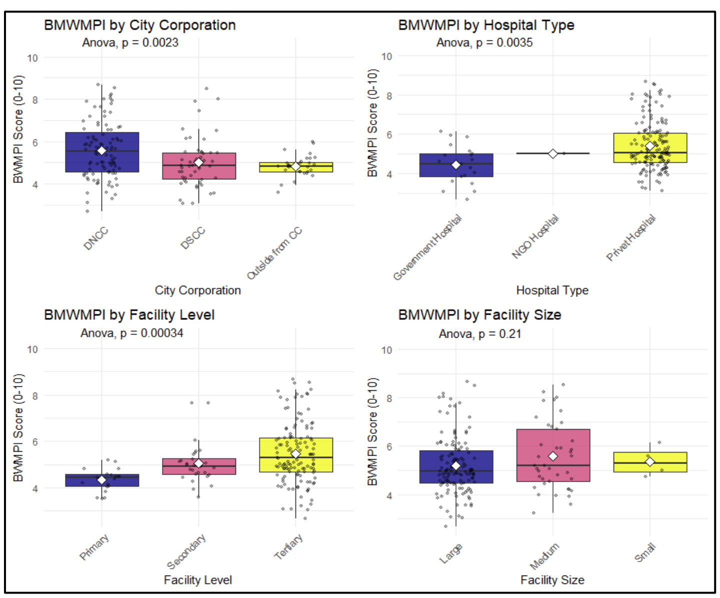

Fig.6. Significance of Geographical disparities, institutional, and functional factors on BMWM PI

Post-hoc comparisons using Tukey's HSD test revealed that the geographic performance gap is driven primarily by the Dhaka North City Corporation (DNCC), which significantly outperformed both the Dhaka South City Corporation (DSCC) (Diff = -0.57, $p = .020$) and peri-urban areas (Diff = -0.74, $p = .009$). No significant difference was found between DSCC and facilities outside the city corporation ($p = .801$), indicating that superior compliance is localized within the DNCC jurisdiction.

Regarding the functional hierarchy of healthcare institutions, a highly significant difference was identified between Tertiary and Primary facilities (Diff = 1.15, $p < 0.001$). While Tertiary facilities scored higher than Secondary ones and Secondary facilities scored higher than Primary ones, these specific pairwise comparisons (Tertiary-Secondary and Secondary-Primary) did not reach statistical significance ($p > 0.05$). This suggests that the critical threshold for effective waste management is tied to the advanced institutional capacity of tertiary centers. Finally, pairwise comparisons for Facility Size remained non-significant across all groups ($p > .05$), confirming that institutional tier and location are more influential predictors of BMWMPI than physical scale.

Multivariate Analysis of BMWM PI Determinants: The predictive capacity and internal drivers of the Bio-medical Waste Management Performance Index (BMWM PI) were evaluated using a Random Forest regression model (N= 500, m = 2). The model demonstrated exceptional robust performance, explaining 92.65% of the total variance in waste management compliance with a low Mean of Squared Residuals (MSR = 0.1116). This high level of explained variance validates the thematic pillars as highly comprehensive indicators of institutional performance, capturing the complex, non-linear relationships inherent in healthcare environmental management.

Variable importance was assessed using Percent Increase in Mean Squared Error (%IncMSE) and Increase in Node Purity, revealing a distinct hierarchy of performance drivers. P3 emerged as the most critical predictor of the overall index (%IncMSE = 39.14), suggesting that the presence of secured perimeters and controlled access serves as a primary proxy for institutional compliance. This was closely followed by P2, P4, and P8, which exhibited significant predictive weights ranging from 23.93% to 25.20% IncMSE. The high Node Purity for P2 (52.60) further underscores its role in effectively differentiating between high- and low-performing facilities. In contrast, P6 and P1 contributed the least to the model's predictive power. This analysis identifies a clear "safety-security-characterization" triad that dictates the quality of bio-medical waste management. These results imply that while infrastructure (P5) and general practices (P7) provide a necessary foundation, the factors that ultimately elevate an institution's BMWM PI score are specialized protocols involving environmental containment, biological risk characterization, and occupational safety.

Bio-medical waste management performance in urban healthcare facilities: The findings indicate that bio-medical waste management performance among healthcare establishments in Dhaka City remains at a moderate compliance level, with considerable variability across institutions. The overall BMWM

Performance Index reflects a system in which minimum structural requirements are often met, yet operational execution remains inconsistent. This pattern suggests that BMWM in Dhaka is characterized less by an absence of infrastructure and more by deficiencies in governance, monitoring, and day-to-day compliance, a challenge commonly reported in rapidly urbanizing health systems within low- and middle-income countries.

Structural capacity institutional and ownership-based differences in BMWM performance: Significant differences in BMWM performance were observed across institutional types. Private healthcare establishments consistently outperformed government hospitals, while tertiary-level institutions demonstrated higher compliance than primary facilities. The underperformance of large public medical colleges is particularly concerning, as these institutions generate high volumes of hazardous waste and serve large patient populations. These disparities likely stem from differences in administrative autonomy, resource flexibility, and enforcement mechanisms, highlighting systemic challenges within public-sector healthcare waste governance.

Geographic disparities and urban governance context: Geographic variation in BMWM performance underscores the role of urban governance and municipal capacity. Healthcare facilities located within Dhaka North City Corporation exhibited significantly higher compliance than those in Dhaka South City Corporation and peri-urban areas. This spatial disparity may reflect unequal regulatory enforcement, differences in municipal waste collection efficiency, and variability in infrastructural maintenance. Such intra-urban inequalities are characteristic of megacities and have important implications for environmental justice and risk concentration in densely populated neighborhoods.

Environmental containment, site security, and external exposure risks: The analysis reveals substantial weaknesses in environmental containment and site security, as evidenced by widespread animal access, inadequate fencing, and unsecured disposal areas. Strong correlations between animal intrusion, safety hazards, and waste scattering demonstrate that poor containment directly elevates occupational and public health risks. The frequent presence of food vendors and commercial activities near waste disposal sites further amplifies exposure pathways, increasing the likelihood of cross-contamination and community-level health risks.

Occupational safety, public health and relationships among BMWM dimensions: Deficiencies in occupational safety practices represent one of the most critical findings of this study. The high prevalence of exposed sharps and minimal use of personal protective equipment among waste handlers significantly increases the risk of needle-stick injuries and blood-borne infections. These hazards extend beyond healthcare workers to include waste collectors, informal scavengers, and nearby residents, reinforcing the need to conceptualize BMWM as a public health priority rather than a purely institutional responsibility.

Correlation analyses highlight the interconnected nature of BMWM components. Poor waste characterization and segregation were strongly associated with increased safety hazards and environmental exposure.

Conversely, standardized management practices were inversely related to animal access and safety risks, confirming their protective role. These findings emphasize that BMWM functions as an integrated system in which weaknesses in one dimension rapidly undermine overall performance.

Key predictors of BMWM performance: insights from multivariate analysis: The Random Forest analysis identifies site security, biomedical waste characterization, animal access control, and safety measures as the most influential predictors of overall BMWM performance. This "safety–security–characterization" framework distinguishes high-performing institutions from low-performing ones and underscores the importance of institutional discipline and enforcement over physical scale. The limited influence of facility size further indicates that management quality and governance capacity are more critical determinants than hospital volume or bed capacity.

Policy and Management Implications for Urban Healthcare Systems: The findings suggest that improving BMWM in Dhaka City requires a strategic shift from infrastructure-driven interventions toward enforcement-oriented and behavior-focused approaches. Regulatory authorities should strengthen monitoring, integrate BMWM indicators into hospital accreditation systems, and enforce penalties for non-compliance. Hospital administrators, particularly within the public sector, should prioritize staff training, internal audits, and clear accountability mechanisms. Municipal coordination is also essential to regulate commercial activities near healthcare facilities and reduce community exposure risks.

CONCLUSION

The study demonstrates that bio-medical waste management (BMWM) performance across healthcare establishments in Dhaka City is highly variable, with overall compliance at a moderate level. Private and tertiary-level institutions consistently outperformed government hospitals and lower-tier facilities, indicating that institutional capacity, governance, and resource availability are critical determinants of effective BMWM. Geographic disparities were evident, as facilities within Dhaka North City Corporation achieved higher compliance than those in Dhaka South City Corporation and peri-urban areas, highlighting the role of municipal oversight and infrastructural support in promoting waste management standards.

Critical gaps remain in waste segregation, site security, occupational safety, and environmental containment, exposing healthcare workers, waste handlers, and nearby communities to significant health and environmental risks. Animal and bird intrusion, poorly secured disposal areas, and proximity of commercial activities amplify exposure pathways, while low use of personal protective equipment underscores systemic weaknesses in occupational safety practices.

These findings have important policy and practical implications. Strengthening regulatory enforcement, standardizing management protocols, improving staff training, and integrating BMWM indicators into hospital accreditation systems are essential for reducing health risks and improving environmental safety. Municipal authorities must prioritize consistent monitoring and address intra-urban disparities to ensure equitable compliance across healthcare facilities.

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