Environ Health Eng Manag 2026;13:1606
http://ehemj.com

doi:10.34172/EHEM.1606

Environmental Health Engineering and Management Journal

Original Article

Environmental Health Engineering and Management

Open Access Publish Free

A Sustainable Approach to Medical and Non-Medical Waste Management in The Expansion of a Central Brain Hospital

Poerna Sri Oetari[1], Ekannisa Jasmiene[2], Umi Kulsum[3,4], Slamet Isworo[4*]

[1]Department of Public Health, Universitas Dian Nuswantoro, Semarang, Indonesia
[2]Doctoral Program in Urban and Regional Planning, Diponegoro University, Semarang, Indonesia
[3]The Sanitation Department, National Brain Center Hospital Prof. Dr. dr. Mahar Mardjono, Jakarta, Indonesia
[4]Department of Environmental Health, Universitas Dian Nuswantoro, Semarang, Indonesia

Abstract

Introduction: The expansion of the Brain Center Hospital is expected to increase medical and non-medical waste by 210.38%. Given current limitations in single-use reliance, bin availability, and storage capacity, this study introduces a predictive statistical and spatial framework with IoT-supported monitoring to strengthen sustainable, regulation-compliant waste management.

Methods: Waste generation and patient load data (2018–2024) were analyzed through linear regression, Pearson's correlation, and Shapiro–Wilk testing, with spatial patterns and hotspots identified using the Shoelace Formula and Kernel Density Estimation.

Results: Waste generation is projected to increase by 210.38% post-expansion, with inpatient medical waste contributing 87.59 kg/day. Patient volumes nearly doubled, showing a very strong correlation with waste generation ($r > 0.98$). Current infrastructure, including 1,026 waste bins and temporary storage capacity of only 30–150 L, is insufficient to meet future demands. Hotspot analysis identified critical waste-generation areas in the inpatient, ICU, and laboratory units.

Conclusion: Hospital expansion without proportional waste management improvements risks regulatory non-compliance and environmental harm. This study proposes a scalable framework integrating predictive modeling, spatial planning, and IoT-enabled monitoring. The novelty lies in combining statistical forecasting, geospatial analysis, and sustainability-oriented solutions to guide policymakers and healthcare providers. While locally applied, the framework is globally relevant and requires validation in diverse hospital contexts to support resilient and sustainable healthcare systems.

Keywords: Medical waste, Waste management, Spatial analysis, Remote sensing technology, Sustainable Development

Citation: Oetari PS, Jasmiene E, Kulsum U, Isworo S. A sustainable approach to medical and non-medical waste management in the expansion of a central brain hospital. Environ Health Eng Manag 2026;13:1606. doi:10.34172/EHEM.1606

Article History:
Received: April 28, 2025
Revised: August 26, 2025
Accepted: September 3, 2025
ePublished: October 5, 2026

***Correspondence to:**
Slamet Isworo, Email:
slametisworo512@gmail.com

Introduction

Hospitals are fundamental components of healthcare systems, not only providing treatment but also contributing to disease prevention, biomedical research, and professional training. In Indonesia, the Ministry of Health regulates hospital operations and classifies facilities by size and specialization to ensure equitable access and service efficiency (1,2). In recent years, the increasing prevalence of neurological disorders has intensified the demand for specialized medical services, creating pressure on existing facilities. To address this growing challenge, the Indonesian government has invested heavily in hospital infrastructure to expand capacity, improve service quality, and ensure accessibility of advanced neurological care (3).

A strategic example of this national initiative is the planned expansion of the Brain Center Hospital in Jakarta. The project is expected to substantially strengthen neurological healthcare in the country by increasing patient capacity, upgrading medical facilities, and improving treatment outcomes (4). Beyond clinical benefits, however, the expansion poses substantial environmental challenges. Anticipated impacts include a sharp rise in medical and non-medical waste, increased emissions from incineration, risks of water contamination, and the potential for social conflict if waste management practices fail to comply with regulatory standards or raise public concerns (5). These challenges underscore the need for a systematic and sustainable approach to hospital waste management during infrastructure expansion.

Hospitals worldwide generate large volumes of waste with heterogeneous characteristics in terms of composition, quantity, and hazardous potential. For example, a study

© 2026 The Author(s). Published by Kerman University of Medical Sciences. This is an open-access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

at Gustavo Lanatta Lujan Hospital reported an average solid waste generation of 92.77 kg/day, consisting of 62.26% biocontaminated waste, 26.45% general waste, 7.7% sharps, and 3.6% special waste. Similarly, research in four hospitals in Dar es Salaam documented medical waste generation ranging from 298.9 to 1,554.4 kg/day, with sharps alone contributing between 8.5 ± 2.7 and 13.9 ± 1.8 kg/day (6). Without effective management, this growth in waste generation can create serious health and ecological risks. Essential measures include strict source segregation, environmentally sound treatment technologies, and compliance with regulatory standards (7). Yet, in many developing countries, inadequate segregation practices lead to greater volumes of hazardous waste, higher disposal costs, and increased risks of environmental contamination. These systemic weaknesses emphasize the importance of strengthening hospital waste management to ensure both public health protection and environmental sustainability.

Predictive analysis has therefore emerged as an essential tool for anticipating waste generation and supporting sustainable waste management strategies (8). Accurate forecasting facilitates more efficient resource allocation, optimal planning of temporary storage facilities, enhancement of segregation practices, and the adoption of advanced treatment technologies. Complementary measures—such as recycling non-hazardous waste and environmentally responsible disposal of hazardous waste through incineration or autoclaving—can further improve system performance (9). Nevertheless, despite progress in both policy and practice, a significant knowledge gap remains in integrating predictive modeling, spatial analysis, and real-time monitoring into hospital waste management. This gap is particularly evident in rapidly expanding healthcare systems of developing countries, where infrastructure growth frequently outpaces the implementation of sustainable waste management solutions (10).

This study hypothesizes that hospital expansion without proportional improvements in waste infrastructure will lead to regulatory non-compliance and environmental risks, while predictive and spatial approaches can provide scalable solutions. To address this, a novel framework is developed that integrates predictive statistical modeling, spatial analysis, and IoT-based monitoring with sustainability-oriented strategies such as Zero Waste principles and CNG-based thermal substitution. Unlike previous studies that focused only on waste quantification or treatment technologies in isolation, this framework links patient volume, waste generation, and spatial infrastructure into a unified predictive system. Applied to the Brain Center Hospital expansion in Indonesia, the model not only addresses national healthcare challenges but also provides globally relevant insights for sustainable hospital waste management in developing countries.

Table 1. Comparison of Existing and Planned Hospital Facilities

Parameter	Existing (Built)	Expansion (Planned)
Planning Area (m²)	11,664	25,464
Ground Floor Area (m²)	5,442.32	9,607.92
Total Floor Area (m²)	36,277.24	112,597.91
Building Coverage Ratio (%)	46.65	33.73
Floor Area Ratio	3.11	2.52
Building Height (floors)	16	12 (53.6 m)
Parking Capacity (cars)	360	430
Green Space Ratio (%)	21.69	49.17
Basement Footprint Ratio (%)	11.61	9.63

Materials and Methods

The sample comprised 2,555 daily records of patient volume and waste generation collected from hospital records between 2018 and 2024. Data were selected purposively as they represent longitudinal patterns before and during hospital expansion.

Study location and site description

This study was conducted at the National Brain Center Hospital (RSPON), encompassing the existing facility and a planned 25,464 m² westward expansion designed to increase patient capacity, optimize service flow, and enhance healthcare quality through sustainable infrastructure (Table 1; Figure 1). Planned developments include new inpatient and outpatient buildings, laboratories, support service units, green open spaces, and expanded parking facilities. The spatial extent of the study area was delineated using 27 GPS-based coordinate points (T1–T27), which were connected to form a closed polygon representing the analytical study-area boundary (Supplementary Figure S1). This polygon provided the geospatial framework for subsequent spatial analyses. Simulated waste-generation hotspots in the ICU, laboratory, inpatient, and outpatient areas were subsequently identified using Kernel Density Estimation (KDE), with the resulting hotspot distribution presented in Figure 2

The RSPON study area was delineated using 27 GPS-based coordinate points (T1–T27), which were connected to form a closed polygon providing the geospatial framework for subsequent spatial analyses (Supplementary Figure S1). This boundary represents the analytical extent of the study area rather than a legal or cadastral boundary. Using this spatial framework, waste-generation patterns in critical service areas, including the ICU, laboratory, inpatient, and outpatient units, were subsequently analyzed using Kernel Density Estimation (KDE), with the resulting hotspot distribution presented in Figure 2.

Land area estimation using shoelace formula

Preliminary area estimation was conducted using either geodetic or projected polygonal calculations within a GIS environment, contingent upon the coordinate reference system applied. For planar projections such as UTM, the estimation process utilizes a closed line integral formulation derived from Green's Theorem:



Figure 1. Map of the Brain Hospital Expansion Site

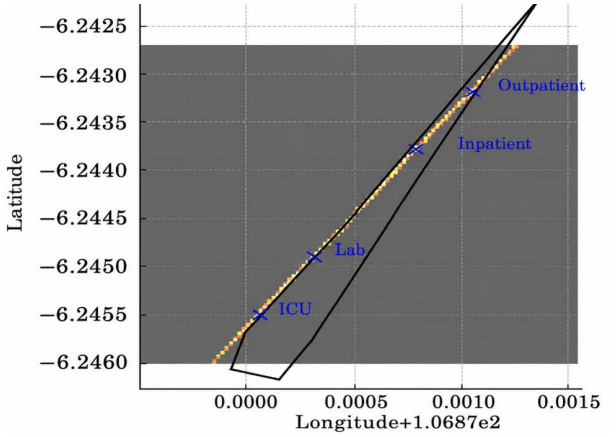


Figure 2. Kernel Density Estimation of Simulated Waste Hotspots

ŭŭŭŭ ∮(−)

The formula $A = 12\oint(x\,dy - y\,dx)$ derived from Green's Theorem computes the area of a planar region by integrating around a closed curve in a counterclockwise direction. Here, xxx and yyy are Cartesian coordinates, with dxdxdx and dydydy as their differentials. The term ((x dy−y dx)) represents elemental areas whose integral yields the total enclosed area. This formulation applies to projected planar systems, whereas geographic coordinates (latitude–longitude) require geodetic algorithms such as Vincenty, Karney, or Hubeny to account for Earth's curvature.

(11). These geodetic methods are automatically implemented in Geographic Information Systems (GIS) software to generate accurate preliminary area estimates, which may then be validated using numerical methods if required (12).

$$\text{Area} = \frac{1}{2}[\sum_{i=1}^{n}(XiYi + 1 - XiYi)]$$

Note:

a) (x1, y1),(x2, y2),…,(xn, yn)(x_1, y_1), (x_2, y_2), …, (x_n, y_n)(x1, y1),(x2, y2),…,(xn, yn) represent the coordinates of the polygon's vertices,
b) (xn + 1, yn + 1) = (x1, y1)(x_{n + 1}, y_{n + 1}) = (x_1, y_1)(xn + 1, yn + 1) = (x1, y1), ensuring closure of the polygon.
c) The summation cycles through each vertex to calculate the total enclosed area

This method enables precise measurement of land allocations and is essential for evaluating land use ratios, such as:

Comparison Ratio = [Existing Area/Development Area]

This spatial computation supports proportional zoning of healthcare infrastructure in alignment with environmental and architectural standards.

Waste volume forecasting using linear regression

To forecast medical and non-medical waste generation following the hospital expansion, Simple Linear Regression (SLR) was employed. The relationship between patient volume (independent variable) and daily waste output (dependent variable) was modelled as follows (13):

$$Y = a + bX$$

where *Y* is the projected waste volume (in kg/day or m^3/day), *X* is the number of patients (inpatients and outpatients), *a* is the intercept (baseline waste generation), and *b* represents the slope coefficient indicating waste increase per additional patient.

The analysis utilized seven years of hospital records (2018–2024), comprising 2,555 daily observations of patient volume and corresponding waste generation. Parameters were estimated using regression analysis, with model fit validated via R^2, residual analysis, and *P* values. To ensure robustness, confidence intervals for

regression coefficients and effect size measures were calculated. Regression and residual plots supported model interpretation, strengthening the predictive validity of the model (14).

Spatial distribution of waste using kernel density estimation (KDE)

To identify spatial patterns of waste generation within the hospital complex, Kernel Density Estimation (KDE) was employed. KDE transforms discrete spatial points into a continuous surface, effectively illustrating waste concentration hotspots. The formula is given as (15).

$$f(x) = 1/nh\sum_{k=1}^{n} K\left(\frac{x - x1}{h}\right)$$

where *f(x)* represents the estimated waste density at location xxx, *n* is the number of spatial data points, *K* is the kernel function (typically Gaussian), *h* is the bandwidth parameter controlling smoothing.

KDE maps were generated using GIS software to visualize high-density waste zones- such as intensive care units (ICUs), laboratories, and outpatient departments- which inform the strategic placement of waste bins, sterilizers, and cold storage units. KDE facilitates effective waste segregation and supports logistics optimization in spatially constrained healthcare environments.

Statistical validation using pearson correlation analysis

Pearson's correlation was used to examine the linear relationship between patient volume and waste generation after normality was confirmed with the Shapiro–Wilk test (16).

$$r = \frac{n\sum XY - (\sum X)(\sum X)}{\sqrt{\left[n\sum x^2 - (\sum x)^2\right]\left[n\sum y^2 - (\sum x)^2\right]}}$$

Where *r* is Pearson's correlation coefficient, *n* is the number of paired observations, *X* is patient volume (daily or annual, inpatient/outpatient), and *Y* is corresponding waste volume (kg/day or m^3/day).

All statistical results were reported with *P* values and 95% confidence intervals. The Shapiro–Wilk test confirmed data normality, while Pearson's correlation revealed a very strong positive linear relationship between patient volume and waste generation ($r > 0.99$; $P < 0.001$). Linear regression was thus validated as reliable, further supported by paired t-tests, R^2 values, confidence intervals, and effect size measures, establishing both statistical significance and practical relevance.

Results

The hospital's waste segregation and initial storage systems are effectively integrated and fully compliant with national regulations, thereby enhancing operational efficiency and ensuring infrastructure readiness to accommodate the projected increase in medical and non-medical waste resulting from service expansion.

Spatial delineation and hotspot analysis of waste generation in the national brain center hospital

The spatial extent of the National Brain Center Hospital (RSPON) study area was delineated using 27 GPS-based coordinate points (T1–T27), which were connected to form a closed polygon encompassing the existing hospital facility and the planned expansion area (Supplementary Figure S1). This polygon represents the analytical extent of the study area rather than a legal or cadastral boundary and provided the geospatial framework for subsequent spatial modelling and waste-management planning. Within this spatial framework, Kernel Density Estimation (KDE) was applied to assess the relative spatial concentration of simulated waste generation across key service areas. The analysis identified four major simulated waste-generation hotspots located in the ICU, laboratory, inpatient, and outpatient units (Figure 2). These hotspots represent areas of relatively high modelled waste concentration, reflecting spatial variations in patient load and the intensity of healthcare activities. From an operational perspective, the identified hotspots indicate priority areas for optimizing waste-bin allocation, infectious-waste storage planning, collection logistics, and IoT-supported monitoring to support more efficient and adaptive hospital waste-management practices.

Evaluation of waste segregation and initial storage system

The Brain Center Hospital has implemented a comprehensive waste management system featuring risk-based segregation, source-level sorting, and strategic bin allocation to meet post-expansion operational demands. A total of 1,026 waste bins comprising 220 for medical waste and 806 for non-medical waste have been deployed in accordance with national standards (17,18).

Table 2 shows critical bin deficits, particularly BIN 1 (–462) and BIN B3-1 (–86). A perfect negative correlation with projected needs ($r = -1.0000$) indicates systemic undersupply. In contrast, BIN 3-3 demonstrates near-perfect alignment with demand ($r = 0.9998$) and a strong inverse relation with deficits ($r = -0.9999$), validating its strategic role in adaptive, risk-based allocation.

Table 2 indicates substantial bin deficits, particularly for BIN 1 (–462 units) and BIN B3-1 (–86 units). Correlation analysis showed near-perfect associations among projected need, deficit, and BIN 3-3 support ($|r| \geq 0.9998$; $P < 0.001$), which are interpreted descriptively because these variables are operationally interdependent.

Temporary-storage requirements varied across waste categories, with infectious and residual waste showing the highest storage-volume demands. The reported capacity-demand indicator does not represent actual on-site storage duration; detailed waste-specific storage requirements are provided in Supplementary Table S1. Descriptive statistics of storage volume, capacity-demand indicators, and footprint requirements are summarized in Supplementary Table S2.

Table 3 shows projected increases in storage-volume

and spatial-footprint requirements following hospital expansion, indicating increased pressure on waste-management infrastructure. Proactive capacity scaling is therefore important to maintain regulatory compliance and operational continuity.

Post-expansion projections indicate substantial increases in storage volume and spatial-footprint requirements across hazardous and non-hazardous waste categories, with most increases of approximately 110%. Detailed waste-type-specific changes in waste volume, storage requirements, and footprint area are presented in Supplementary Table S3.

Table 4 summarizes the statistical relationships among projected waste-management parameters. Footprint area showed a significant increase ($P = 0.0036$; d = 0.75), whereas changes in waste volume ($P = 0.059$; d = 0.42) and storage volume ($P = 0.091$; d = 0.38) did not reach conventional statistical significance. Waste volume was moderately correlated with storage volume (r = 0.546; $P = 0.054$), while no significant correlation was observed with footprint area (r = 0.043; $P = 0.889$). Regression analysis identified patient volume as the strongest predictor ($\beta = 0.98$; $P < 0.001$), with waste type and spatial allocation also contributing significantly.

Trends in patient numbers and medical & non-medical waste production in healthcare facilities (2018–2024)

Patient volumes and waste generation increased overall from 2018 to 2024, with inpatient daily patient volume

Table 2. Summary of Hospital Waste Bin Capacity and Correlation Analysis Between Projected Needs, Deficits, and BIN 3-3 Support

Bin Type	Purpose	Volume / Unit	Placement Area	Current Qty	Projected Need	Deficit	BIN 3-3 Support	Total After Support
BIN B3-1	Infectious, sharp, anatomical	1 × 36 L	Waste room	154	240	–86	90	244
BIN B3-2	Chemical, pharmaceutical, etc.	1 × 30 L	Waste room	66	102	–36	40	106
BIN 1	Inorganic	1 × 30 L	Indoor	768	1,23	–462	500	1,268
BIN 2	Organic + residue	3 × 50 L	Outdoor	9	15	–6	8	17
BIN 4	Organic & inorganic	2 × 30 L	Pantry	29	44	–15	20	49

Noted: The analysis shows perfect negative correlations between projected need and deficit (r = –1.0000) and between support and deficit (r = –0.9999), alongside a near-perfect positive correlation with BIN 3-3 support (r = 0.9998), all highly significant ($P < 0.001$)

Table 3. Calculation of Predicted Temporary Hazardous Waste Storage Capacity Before and After Expansion, Based on Standard Waste Generation Rates (MoH Regulation No. 7/2019) (19)

Waste Category	Waste Type	Storage Volume (L) Existing	Storage Volume (L) Expanded	Footprint (m²) Existing	Footprint (m²) Expanded	% Increase	Collection Facility
Hazardous	Used Oil/Lubricants	253	531	1.57	3.30	110%	200 L Drum
	B3 Packaging Waste	201	422	3.87	8.14	109%	200 L Drum
	Solid (Toxic B3)	201	422	19.20	40.39	110%	200 L Drum
	E-waste	927	1,951	19.20	40.39	110%	200 L Drum
	Medical Heavy Metals	28	59	20.23	42.56	111%	Cold Storage
	Infectious Waste	15,569	32,755	20.23	42.56	110%	Cold Storage
	Cytotoxic Waste	205	431	3.14	6.61	110%	200 L Drum
Non-Hazardous	Organic Waste (Food)	1,418	2,984	2.83	6.00	111%	Trolley 1100 L
	Organic Waste (Tree)	1,288	2,709	2.83	6.00	110%	Trolley 1100 L
	Inorganic Waste (Paper)	990	2,083	1.42	3.00	111%	Trolley 1100 L
	Inorganic Waste (Plastic)	1,011	2,126	1.42	3.00	110%	Trolley 1100 L
	Inorganic Waste (Glass/Metal)	149	314	1.42	3.00	111%	Trolley 1100 L
	Residual Waste	6,754	14,21	9.91	20.80	110%	Trolley 1100 L

Table 4. Statistical and Multivariate Analysis on Waste Generation

Analysis Type	Parameter/Variable	Statistic (t/r/β)	*P*-value	95% CI	Effect Size	Interpretation
Paired t-test	Waste Volume	t = –2.09	0.059	[–3.21, 0.08]	d = 0.42	Nearly significant, small–medium effect
Paired t-test	Storage Volume	t = –1.84	0.091	[–2.95, 0.24]	d = 0.38	Not significant, small effect
Paired t-test	Footprint Area	t = –3.61	0.0036	[–4.89, –1.27]	d = 0.75	Highly significant, medium–large effect
Pearson Correlation	Waste Volume vs Storage Volume	r = 0.546	0.054	[0.12, 0.81]	$r^2 = 0.30$	Moderate correlation, nearly significant
Pearson Correlation	Waste Volume vs Footprint Area	r = 0.043	0.889	[–0.42, 0.49]	$r^2 = 0.002$	No significant correlation
Multivariate Regression	Patient Volume	β = 0.98	<0.001	[0.88, 1.08]	$\eta^2 = 0.82$	Strong, highly significant predictor
Multivariate Regression	Waste Type (Medical/Non-medical)	β = 0.42	0.004	[0.19, 0.65]	$\eta^2 = 0.31$	Moderate effect, significant
Multivariate Regression	Spatial Allocation (KDE Hotspots)	β = 0.28	0.009	[0.10, 0.46]	$\eta^2 = 0.22$	Significant spatial effect

Note: All statistical tests are reported with p-values and 95% confidence intervals

increasing from 29 to 65 and outpatient volume from 70 to 137. Detailed annual trends in patient numbers and medical and non-medical waste production are presented in Supplementary Table S4. Patient–waste associations were consistently strong across the evaluated measures (r = 0.980–1.000), with the detailed correlation results presented in Supplementary Table S5.

Table 5 summarizes the scale-dependent relationship between patient volume and waste generation. Daily data showed a very strong positive correlation (r = 0.99; $P < 0.001$), whereas annual correlations were weak (r = 0.19–0.28; n.s.), indicating that higher-frequency data may provide a more stable basis for short-term predictive planning.

Across 2018–2024, medical waste accounted for an average of 59.3% of inpatient waste and 92.4% of outpatient waste, while the corresponding non-medical fractions were 40.7% and 7.6%. Annual proportions are presented in Supplementary Table S6. Comparative reference information and variability statistics are provided in Supplementary Tables S7 and S8, respectively.

Comparative and variability analyses further show a consistently high proportion of medical waste in outpatient services and relatively low year-to-year variability in the reported waste composition. Benchmark comparisons and descriptive variability statistics are provided in Supplementary Tables S7 and S8, respectively.

Table 5. Summary of Correlation Analysis between Patient Trends and Waste Production (2018–2024)

Scale of Data	Correlation (r)	Significance	Interpretation
Daily (2018–2024)	0.99	$P < 0.001$	Very strong, significant
Annual (2018–2024)	0.19–0.28	n.s.	Weak, unstable

Table 6. Projected Medical and Non-Medical Waste Generation After Hospital Expansion

Parameter	Current Total (Year)	Current Total (Day)	Predicted Total (Year)	Predicted Total (Day)	% Increase
Patients					
Avg. Inpatient Patients	45,029	123.4	94,732	259.5	110%
Avg. Outpatient Patients	101,369	277.7	213,260	584.3	111%
Medical Waste (kg)					
Inpatient	18,011	49.3	37,893	103.8	111%
Outpatient	12,672	34.7	26,653	73.0	110%
Non-Medical Waste (kg)					
Inpatient	29,269	80.2	61,576	168.7	110%
Outpatient	1,014	2.8	2,133	5.8	110%
Medical Waste (m^3)					
Inpatient	2,702	7.4	5,684	15.6	111%
Outpatient	1,901	5.2	3,999	11.0	110%
Non-Medical Waste (m^3)					
Inpatient	2,927	8.0	6,158	16.9	111%
Outpatient	102	0.3	214	0.6	110%

Table 6 presents the projected post-expansion generation of medical and non-medical waste, reaching approximately 176.8 and 174.5 kg/day, respectively. These projections indicate a substantial increase in waste-management demands and underscore the need for scalable handling, storage, and treatment capacity.

These projected increases emphasize the importance of aligning waste-management capacity with the anticipated growth in hospital services.

Table 7 indicates that CNG represents a balanced post-expansion boiler option among the alternatives evaluated. It has the lowest monthly operating cost, a lower initial investment and shorter estimated ROI than the electric boiler, and favorable emissions, fire-risk, and maintenance characteristics compared with the other options. These operational, economic, and environmental considerations support the selection of CNG as a suitable option for the hospital's post-expansion energy system.

Theoretical simulation for generalizability

An exploratory simulation was conducted to assess the potential scalability of the proposed framework to Type B (≈ 800 patients/day) and Type C (≈ 300 patients/day) hospitals. Baseline waste generation was estimated using the average slope of 0.95 kg/patient derived from the primary model. Scenario analyses were then applied for enhanced waste segregation, full IoT-based monitoring, and CNG-based energy substitution using literature-informed assumptions (13,20-23). These simulations were designed to examine potential transferability across hospital scales rather than to provide external empirical validation.

The simulated scenarios showed consistently strong patient–waste relationships ($r \geq 0.95$; $R^2 \geq 0.90$) across both hospital types and indicated potential improvements in waste reduction, overflow prevention, and energy performance under the evaluated management scenarios. Detailed assumptions, hospital-specific hotspot patterns, and scenario outcomes are presented in Supplementary Table S9. Because these results are simulation-based, they should be interpreted as evidence of potential scalability rather than confirmed generalizability.

Table 7. Comparative Evaluation of Boiler Alternatives for Hospital Energy Efficiency

Criteria	Diesel (Solar)	CNG	Electric Boiler
Initial Investment (IDR)	-	1,930,000,000	3,180,000,000
Monthly Cost (IDR)	264,000,000	153,000,000	660,000,000
ROI (Months)	-	13	19
Mean		2,555,000,000	
Min		1,930,000,000	
Max		3,180,000,000	
Standard Deviation		620,000,000	
Emissions	High	Low	Dependent on Grid Source
Fire Risk	Medium–High	Low	Low
Maintenance	High	Low	Moderate

Discussion

Integrated infrastructure optimization and spatial planning

An analysis of the existing infrastructure and planned expansion (Table 1) highlights an integrated spatial strategy that emphasizes land-use efficiency, environmental sustainability, and expanded healthcare capacity in line with Indonesia's National Health System Transformation Agenda. Optimization of key indicators such as the Building Coverage Ratio (BCR), Green Space Ratio (GSR), and Floor Area Ratio (FAR) ensures compliance with national standards, including the Ministry of Health Regulation No. 24/2016, which mandates at least 30% green open space (24). The increase of GSR to over 49% demonstrates strong institutional commitment to green hospital principles, consistent with climate-resilient infrastructure strategies that enhance ecological, psychosocial, and physical well-being. Simultaneous reductions in BCR and FAR minimize land-use pressure while improving ecological functions such as water infiltration, natural lighting, ventilation, and universal accessibility. Furthermore, structural modifications—including vertical expansion, parking improvements, and utility upgrades—comply with PUPR Regulation No. 21/2021 and national green retrofitting guidelines, reinforced by ISO 14001:2015 standards, thereby ensuring sustainability across hospital infrastructure systems (25).

Complementing this infrastructure framework, spatial delineation using 27 GPS-based coordinate points provided a precise geospatial boundary for the National Brain Center Hospital (RSPON), covering both existing facilities and the planned expansion area. This delineation formed the foundation for spatial modeling and waste management planning. Kernel Density Estimation (KDE) analysis subsequently identified four critical waste-generation hotspots concentrated in the ICU, laboratory, inpatient, and outpatient units. These concentrations are consistent with the high patient load and intensive medical activities in these departments, underscoring the need for spatially prioritized waste management strategies rather than uniform approaches across the facility. Importantly, both the delineation process and hotspot-based waste planning were conducted in accordance with Indonesian regulations, particularly Ministry of Environment and Forestry Regulation No. 56/2015 on infectious medical waste storage and Ministry of Health Regulation No. 7/2019 on healthcare facility waste management (26,27).

The practical implications include the targeted allocation of medical waste bins, the expansion of temporary cold storage for infectious waste, and the adoption of IoT-based monitoring systems to prevent overflow while ensuring compliance with both health and environmental regulations. Taken together, the integration of sustainable infrastructure indicators (BCR, GSR, FAR) with geospatial hotspot analysis provides a transferable and regulation-compliant framework. This model not only advances the green hospital agenda but also offers a scalable and replicable approach for hospitals in other middle-income countries undergoing rapid expansion and rising patient demand (28).

Strategic waste bin allocation and adaptive infrastructure

The expansion of the Brain Center Hospital highlights challenges in bin adequacy, storage capacity, and waste segregation. Despite the deployment of 1,026 bins, deficits remained across several categories, indicating the need for adaptive allocation strategies. Baseline temporary-storage requirements are detailed in Supplementary Tables S1–S2, while waste-type-specific post-expansion storage and footprint projections are provided in Supplementary Table S3. Post-expansion requirements generally increased by approximately 110%, with footprint area increasing significantly ($P = 0.0036$; $d = 0.75$) and patient volume emerging as the strongest predictor of waste generation ($\beta = 0.98$; $P < 0.001$) (Table 4) (26).

Medical and non-medical waste generation is projected to reach approximately 176.8 and 174.5 kg/day, respectively (Table 6), emphasizing the need for scalable handling, storage, and treatment capacity (29). Waste-composition data further showed that outpatient medical waste averaged 92.4%, whereas inpatient non-medical waste averaged 40.7% (Supplementary Tables S6–S8), supporting waste-specific infrastructure planning. Among the evaluated boiler alternatives, CNG provided the lowest monthly operating cost and favorable investment, ROI, emissions, fire-risk, and maintenance characteristics relative to the electric option (Table 7). Collectively, these findings support an integrated framework combining predictive modelling, adaptive bin allocation, scalable storage, spatial planning, and digital monitoring (23).

Deficits, statistical correlations, and multifunctional compensation strategies in hospital waste management

Predictive Waste Modeling and Adaptive Regulatory Strategies

A comprehensive understanding of waste-generation dynamics is critical for designing sustainable and resilient waste-management systems, particularly in large healthcare facilities undergoing expansion. Between 2018 and 2024, the Brain Center Hospital exhibited a marked increase in medical and non-medical waste generation concurrent with rising patient volumes (Supplementary Table S4). At the daily scale, patient volume showed consistently strong associations with waste generation ($r = 0.980–1.000$; $P < 0.001$; Supplementary Table S5), indicating its utility as a predictor for short-term planning of waste-handling capacity, bin allocation, and operational logistics. At the annual scale, however, correlations were substantially weaker ($r = 0.19–0.28$; n.s.; Table 5), suggesting that longer-term linear relationships are less stable and may be influenced by temporal disruptions, including the COVID-19 pandemic, policy changes, and shifts in healthcare service delivery. Waste-composition analysis further showed that outpatient medical waste increased from 9 to 17 kg/day and accounted for an average of

92.4% of total outpatient waste, exceeding the comparative reference range of 75–80%. Inpatient non-medical waste accounted for an average of 40.7%, indicating substantial opportunities for improved material recovery and recycling. Adaptive measures, including cold storage for infectious waste, 1,100-L trolleys, and source-specific bin allocation, demonstrate the practical application of predictive insights to waste-management planning. To strengthen operational resilience and regulatory compliance, priority measures include digital waste tracking for real-time monitoring, development of appropriate on-site treatment and recovery capacity, and continuous staff training in waste segregation and safe handling. These measures are consistent with relevant international sustainability and healthcare-waste-management principles and support alignment with applicable Indonesian environmental and health regulation (30,31).

The Brain Center Hospital demonstrates strong commitment to improvement and environmental responsibility. Predictive correlations offer useful planning insights but require validation through real-time data and adaptive oversight to ensure compliance and resilience. By translating these correlations into adaptive bin allocation, targeted recycling, and regulatory alignment, this study contributes a sustainable, regulation-compliant model that strengthens institutional resilience while meeting national and international standards (32).

These findings align with prior studies in Peru, Tanzania, and India, which reported variations in waste generation per patient and underscored the value of predictive approaches for sustainable planning. By situating the results within global evidence and literature on Zero Waste, IoT-based monitoring, and carbon reduction, the discussion not only validates patient volume as a predictor but also contextualizes the framework within broader regulatory and sustainability debates. This reinforces the study's recommendations on policy revisions, digital monitoring, and sustainable hospital waste management, ensuring both contextual grounding and international relevance.

Zero waste strategy and carbon emissions reduction

Addressing systemic gaps in Indonesian hospital waste management requires an integrated approach combining risk-based segregation, safe treatment, digital monitoring, material recovery, and appropriate on-site treatment technologies. Transitioning toward a Zero Waste framework further requires circular-economy principles, institutional collaboration, and environmentally sound treatment options, including autoclaving and other non-incineration technologies where technically feasible (33).

For the Brain Center Hospital, projected post-expansion medical and non-medical waste generation reaches approximately 176.8 and 174.5 kg/day, respectively (Table 6), indicating substantially increased waste-management demands. Supporting data include documented bin deficits (Table 2), baseline storage requirements (Supplementary Tables S1–S2), and waste-type-specific post-expansion storage and footprint projections (Supplementary Table S3). Patient–waste trends and associations are detailed in Supplementary Tables S4 and S5, while waste-composition patterns and comparative analyses are provided in Supplementary Tables S6–S8. From a carbon-management perspective, emission-reduction estimates should be interpreted as scenario-based outcomes that depend on waste composition, treatment pathways, and energy-management assumptions(22). Accordingly, these estimates require empirical validation before being interpreted as confirmed reductions. Among the evaluated boiler alternatives, CNG showed favorable operating-cost, emissions, fire-risk, and maintenance characteristics and was therefore considered a suitable post-expansion option under the study assumptions (Table 7). The exploratory simulation further indicated potential CO_2-emission reductions of approximately 28–30% under the CNG substitution scenarios (Supplementary Table S9).

The proposed framework integrates patient volume, waste-generation patterns, spatial infrastructure, treatment planning, and IoT-based monitoring to support more adaptive and resource-efficient hospital waste management. These sustainability-oriented measures are consistent with broader global health-system and Sustainable Development Goal priorities (34).

Theoretical simulation for generalizability

The theoretical simulation summarized in Supplementary Table S9 suggests that the proposed framework may be adaptable to hospitals of different scales in Indonesia. Type B and Type C scenarios showed strong patient–waste correlations ($r \geq 0.95$) and model fit ($R^2 \geq 0.90$). Simulated KDE patterns differed by hospital type, with hotspots concentrated in the ICU, laboratory, and outpatient department for Type B hospitals, and in outpatient clinics and pharmacy areas for Type C hospitals.

Scenario testing indicated potential reductions of 20–22% in hazardous waste, 55–60% in overflow incidents under IoT monitoring, and approximately 32–35% in energy operating costs under CNG substitution. Because these findings are simulation-based, they indicate potential scalability and require external empirical validation before broader generalizability can be established.

Regulatory compliance and innovative amendments

In addition to complying with the Ministry of Environment and Forestry (MOEF) regulations, this study introduces practical innovations derived from empirical findings by establishing thresholds for IoT-enabled bin alerts at critical fill levels, implementing real-time monitoring of temporary storage saturation to prevent overflow, and integrating predictive modeling outputs into operational dashboards, thereby reinforcing regulatory adherence while simultaneously providing data-driven solutions that enhance adaptability, efficiency, and sustainability in hospital waste management.

Novelty statement

The novelty of this study lies in its integrated approach

that simultaneously links patient volume, waste generation, and spatial infrastructure with IoT-based monitoring, Zero Waste strategies, and CNG energy substitution—an intersection rarely addressed in existing hospital waste management research. By further embedding carbon footprint assessment and benchmarking against international standards, this study advances beyond conventional models, offering a regulation-compliant, replicable, and sustainability-oriented framework. The main contribution of this research is the development of a comprehensive and data-driven decision-support model that enables hospitals to anticipate waste trajectories, optimize spatial planning, and align infrastructure development with environmental sustainability goals. This contribution is particularly significant for developing and middle-income countries, where healthcare expansion must be balanced with stringent environmental responsibility, positioning the model as both innovative and globally relevant.

Limitations of the study

This study has several limitations that should be acknowledged. First, demographic and socio-economic variables were not incorporated into the analysis, as the study relied exclusively on secondary data linking patient volume with waste generation between 2018 and 2024. As a result, broader contextual determinants of waste production could not be examined. Second, although the proposed framework was conceptually designed to be scalable, its empirical validation was confined to a single institution—the Central Brain Hospital. This limitation highlights the need for external validation across hospitals of varying sizes, specialties, and ownership structures to substantiate claims of generalizability. Third, the study did not include interviews or surveys with operational staff, thereby constraining the ability to capture behavioral dimensions and day-to-day operational challenges in waste handling and segregation. Such qualitative insights are essential for understanding staff compliance, workload dynamics, and training gaps, all of which critically influence the effectiveness of hospital waste management systems. Future research should therefore integrate predictive and spatial modeling with qualitative methodologies to generate a more comprehensive, behaviorally informed, and operationally grounded framework for sustainable hospital waste management.

Conclusion

The expansion of the Central Brain Hospital is projected to improve national neurological services but will also trigger a 210.38% increase in medical and non-medical waste, closely correlated with patient volume ($r > 0.97$; $P < 0.001$). Existing infrastructure shows major deficits, including over 600 missing bins and limited storage capacity, which is expected to rise by more than 110%. This study proposes an integrated, predictive waste management strategy combining linear regression, spatial modeling (Shoelace Formula, KDE), Pearson's correlation, BIN 3-3 deployment, adaptive storage, and CNG boiler technology. Reinforced by Zero Waste principles, IoT-based tracking, and alignment with national and international standards (MOH Reg. No. 7/2019, MOEF Reg. No. 56/2015, ISO 14001:2015, WHO, Basel Convention), this model offers a scalable, data-driven framework for sustainable hospital infrastructure. The findings provide actionable insights for policymakers and healthcare planners to enhance compliance, resilience, and service sustainability.

Acknowledgements

The author extends sincere gratitude to the Brain Center Hospital, PT Mitra Adhi Pranata, and Universitas Dian Nuswantoro for their invaluable support and collaboration. Special appreciation is also directed to the hospital management team for their commitment to data transparency and operational insights, which were essential to the success of this study. This partnership exemplifies the vital synergy between academia, healthcare institutions, hospital management, and industry in advancing sustainable healthcare systems and environmentally responsible waste management practices.

Authors' Contribution

Conceptualization: Slamet Isworo, Poerna Sri Oetari
Data Curation: Slamet Isworo
Formal Analysis: Slamet Isworo, Ekannisa Jasmiene
Investigation: Umi Kulsum, Slamet Isworo
Methodology: Slamet Isworo, Ekannisa Jasmiene
Project Administration: Poerna Sri Oetari
Resources: Umi Kulsum, Poerna Sri Oetari
Software: Slamet Isworo
Supervision: Poerna Sri Oetari
Validation: Ekannisa Jasmiene, Umi Kulsum
Visualization: Slamet Isworo
Writing–Original Draft: Slamet Isworo, Poerna Sri Oetari
Writing–Review & Editing: Poerna Sri Oetari, Ekannisa Jasmiene, Umi Kulsum

Competing Interests

The authors declare that there are no conflicts of interest related to the publication of this manuscript.

Ethical Approval

This study adhered to all applicable ethical standards. All data collected during the research are original and have not been published or submitted elsewhere.

Funding

This research received no external funding.

Supplementary Files

Supplementary file 1 contains Tables S1-S9 and Figure S1

References

1. Muliarini P, Wiryani F, Nasser M, Najih M. Case management for equitable and excellent hospital services. In: Proceedings of the 3rd International Conference on Indonesian Legal Studies (ICILS 2020). Semarang: European Alliance for Innovation; 2021. doi:10.4108/eai.1-7-2020.2303653
2. Almomani RZ, Al-Ghdabi RR, Banyhamdan K. Patients' satisfaction of health service quality in public hospitals: a PubHosQual analysis. Manag Sci Lett 2020;10(8):1803-12. doi:10.5267/j.msl.2019.12.038
3. Venketasubramanian N, Yudiarto FL, Tugasworo D. Stroke burden and stroke services in Indonesia. Cerebrovasc Dis Extra 2022;12(1):53-7. doi:10.1159/000524161
4. Rilianto B, Kurniawan RG, Rajab NM, Prasetyo BT. Endovascular thrombectomy for acute ischemic stroke in Indonesia: challenging and strategic planning. Neuropsychiatr

Dis Treat 2024;20:621-30. doi:10.2147/ndt.S453629
5. Sijm-Eeken M, Jaspers M, Peute L. Identifying environmental impact factors for sustainable healthcare: a scoping review. Int J Environ Res Public Health 2023;20(18):6747. doi:10.3390/ijerph20186747
6. Suarez Rivadeneira JE, Suarez Chavarry EB, Ramirez ÍM, Camacho WR, Calderón EV, Astonitas RP, et al. Generation rate of hospital solid waste from different services: a case study in the province of Bagua, northern Peru. Heliyon 2024;10(11): e31814. doi:10.1016/j.heliyon.2024.e31814
7. Borowy I. Medical waste: the dark side of healthcare. Hist Cienc Saude Manguinhos 2020;27(Suppl 1):231-51. doi:10.1590/s0104-59702020000300012
8. Alighardashi M, Moein H, Dehghanpour S, Mousavi SA, Almasi A, Mohammadi P. Environmental assessment of hospital waste management practices: a study of hospitals in Kermanshah, Iran. Results Eng 2024;23:102658. doi:10.1016/j.rineng.2024.102658
9. Vallée A. Green hospitals face to climate change: between sobriety and resilience. Heliyon 2024;10(2): e24769. doi:10.1016/j.heliyon.2024.e24769
10. William P, Kuppusamy S, Samundeeswari A, Vijayabharathi R, Hajiyeva RJ, Thangavel K, et al. Integrating IoT and machine learning for real-time monitoring of infectious waste management. In: Kulkarni S, Haghi AK, Egbuchunam TO, Kakodkar S, eds. Hospital Waste Management and Toxicity Evaluation. Hershey, PA: IGI Global Scientific Publishing; 2025. p. 299-320. doi:10.4018/979-8-3693-5757-6.ch011.
11. Windarni VA, Setiawan A, Rahmatalia A. Comparison of the Karney polygon method and the shoelace method for calculating area. Matrik Jurnal Manajemen, Teknik Informatika, dan Rekayasa Komputer 2023;23(1):39-52. doi:10.30812/matrik.v23i1.2929
12. Karney CF. The area of rhumb polygons. Stud Geophys Geod 2024;68(3):99-120. doi:10.1007/s11200-024-0709-z
13. Al-Omran K, Khan E. Predicting medical waste generation and associated factors using machine learning in the Kingdom of Bahrain. Environ Sci Pollut Res 2024;31(26):38343-57. doi:10.1007/s11356-024-33773-1
14. Wikurendra EA, Syafiuddin A, Herdiani N, Nurika G. Forecast of waste generated and waste fleet using linear regression model. Pol J Environ Stud 2023;32(2):1867-76. doi:10.15244/pjoes/158779
15. Zhang S, Ma Y, Ren J, Liu H, Cui L, Fan Z. Research on the spatial allocation of fundamental medical facilities utilizing multi-objective optimization-a case study on Tianjin. J Asian Archit Build Eng 2025:1-23. doi:10.1080/13467581.2025.2527286
16. Zulkipli F, Jamian NH. Correlation and exploratory factor analysis on awareness of solid waste management in Malaysia. Int J Acad Res Bus Soc Sci 2021;11(10):1151-64. doi:10.6007/IJARBSS/v11-i10/11492
17. Hansen S. Construction waste management from environmental law perspective in Indonesia. Int J Law Public Policy 2024;6(1):1-7. doi:10.36079/lamintang.ijlapp-0601.578
18. Ji A, Guan J, Zhang S, Ma X, Jing S, Yan G, et al. Environmental and economic assessments of industry-level medical waste disposal technologies - a case study of ten Chinese megacities. Waste Manag 2024;174:203-17. doi:10.1016/j.wasman.2023.11.036
19. Muhajirin A, Sanjaya R, Hastuti TD, Setianto BD. Analysis of the cultural resilience of health workers in medical waste management at health care facilities. In: Proceedings of the 7th Celt International Conference (CIC 2024). Paris: Atlantis Press; 2024. p. 76-101. doi:10.2991/978-2-38476-348-1_7
20. Singh N, Ogunseitan OA, Tang Y. Medical waste: current challenges and future opportunities for sustainable management. Crit Rev Environ Sci Technol 2022;52(11):2000-22. doi:10.1080/10643389.2021.1885325
21. Oturu K, Ijomah W, Orr A, Verpeaux L, Broadfoot B, Clark S, et al. Remanufacturing of single-use medical devices: a case study on cross-border collaboration between the UK and Nigeria. Health Technol (Berl) 2022;12(2):273-83. doi:10.1007/s12553-022-00641-2
22. Lee SM, Lee D. Effective medical waste management for sustainable green healthcare. Int J Environ Res Public Health 2022;19(22):14820. doi:10.3390/ijerph192214820
23. Ghahramani M, Zhou M, Molter A, Pilla F. IoT-based route recommendation for an intelligent waste management system. IEEE Internet Things J 2021;9(14):11883-92. doi:10.1109/jiot.2021.3132126
24. Sahid, Sumiyati Y, Purisari R. The constrains of green building implementation in Indonesia. J Phys Conf Ser 2020;1485(1):012050. doi:10.1088/1742-6596/1485/1/012050
25. Mkalaf KA, Alshaheen N, Al-Hadeethi RH, Al-Bazi A. Recovery of a green hospital systems based on ISO 14001: 2015 standards. Pesqui Oper 2023;43: e265411. doi:10.1590/0101-7438.2023.043.00265411
26. Prasetyo A, Wahyudianto H, Layuk P, Siswanto S, Nurdin M, Gartika D, et al. Policy adjustment towards green economy in customary territory after the expansion of Papua province. In: Proceedings of the 4th Borobudur International Symposium on Humanities and Social Science 2022 (BIS-HSS 2022). Paris: Atlantis Press; 2023. p. 81-93. doi:10.2991/978-2-38476-118-0_10
27. Çetin E, Hussein A, Güneş-Durak S. Advancing sustainable medical waste management: a case study on waste generation and classification in a university hospital microbiology laboratory. Sustainability 2025;17(10):4325. doi:10.3390/su17104325
28. Xu Z, Rui J. The mitigating effect of green Space's spatial and temporal patterns on the urban heat island in the context of urban densification: a case study of Xi'an. Sustain Cities Soc 2024;117:105974. doi:10.1016/j.scs.2024.105974
29. Gashaw AK, Pitta S, Jifera LD. Assessment of medical waste generation, disposal practices and health implications at Bule Hora University Teaching Hospital, West Guji, Ethiopia. Discov Health Syst 2025;4(1):91. doi:10.1007/s44250-025-00261-3
30. Oladosu OA, Olodo AA, Oloruntoba EA, Opeodu OT, Adegoroye A. Investigation of efforts and problems in implementing the basel convention on the control of transboundary movements of wastes and their disposal in Nigeria. Asian J Geogr Res 2024;7(1):69-84. doi:10.9734/ajgr/2024/v7i1216
31. Simion Luduşanu DG, Fertu DI, Tinică G, Gavrilescu M. Integrated quality and environmental management in healthcare: impacts, implementation, and future directions toward sustainability. Sustainability 2025;17(11):5156. doi:10.3390/su17115156
32. Boudanga Z, Benhadou S, Medromi H. An innovative medical waste management system in a smart city using XAI and vehicle routing optimization. F1000Res 2023;12:1060. doi:10.12688/f1000research.138867.2
33. Alhosani K. Leveraging public-private partnerships for a circular industry economy: advancing economic sustainability in industrial waste management in the Emirate of Ajman, UAE. Challenges 2025;16(3):31. doi:10.3390/challe16030031
34. World Health Organization (WHO). World Health Statistics 2025: Monitoring Health for the SDGs, Sustainable Development Goals. Geneva: WHO; 2025.