SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 2.1, (2026), pp. 231-242
Open Access. Online & Print

DOI: 10.5281/zenodo. 122.12621

ASSESSING THE ENVIRONMENTAL PERFORMANCE OF SOLID WASTE MANAGEMENT SYSTEMS IN A SUPER SPECIALTY HOSPITAL

Rajesh Rajappan Rajamma[1], Damodaran Madhavi Vasudevan[2*], Geena Prasad[3], Ayona Jayadev[4], Pillay V.V[5], Sujatha C.H[6] and Lekha.G[7]

[1]Department of Water Treatment and Biomedical Waste Management, Amrita Institute of Medical Sciences and Research Centre, Amrita Vishwa Vidyapeetham, Kochi Campus-682041, Kerala, India rajeshrr@aims.amrita.edu
[2]Dean, Research, Amrita Institute of Medical Sciences and Research Centre, Amrita Vishwa Vidyapeetham, Kochi Campus-682041, Kerala, India. dmvasudevan@yahoo.co.in
[3]Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, Kerala, India. geena@am.amrita.edu
[4]Research Centre and Post Graduate, Department of Environmental Sciences, All Saints' College, Thiruvananthapuram, Kerala, India, https://orcid.org/0000-0001-7974-8246
[5]Forensic Medicine and Medical Toxicology, Amrita Institute of Medical Sciences and Research Centre, Kochi-682041, Kerala, India, toxicology@aims.amrita.edu
[6]Department of Chemical Oceanography, Cochin University of Science and Technology, Kochi. drchsujatha@yahoo.co.in
[7]Water treatment and Biomedical Waste Management, Amrita Institute of Medical Sciences and Research Centre, Amrita Vishwa Vidyapeetham, Kochi-682041, Kerala, India

Received: 01/12/2025
Accepted: 02/01/2026

Corresponding Author: Damodaran Madhavi Vasudevan (dmvasudevan@yahoo.co.in)

ABSTRACT

Super specialty hospitals are resource-intensive healthcare systems that generate substantial quantities of solid waste, placing significant pressure on environmental management infrastructure and regulatory compliance. As the number of patients and the complexity of services increase, effective waste management has become critical for operational efficiency, environmental safety, and industrial sustainability. This study assesses the performance and operational challenges of solid waste management systems in a 1,300-bed super specialty teaching hospital in South India. The analysis is on secondary operational records of daily solid waste generation between 2022 and 2024. A descriptive and time-series analysis design was employed after systematic data cleaning and validation to examine annual and monthly waste generation trends, per-bed-day waste indices, and temporal fluctuations in waste production. The results reveal that the total waste generation over the three years increased from 133,376 kg/bed/day in 2022 to 144,168 kg/bed/day in 2024, reflecting the growing intensity of healthcare operations and services. The findings highlight critical gaps in the existing practices and underscore the need for data-driven decision-making, improved waste segregation, scalable waste-handling infrastructure, and integrated sustainability planning. This study provides empirical insights that can inform hospital administrators and policymakers in strengthening environmentally

responsible waste management strategies in large super specialty healthcare institutions.

KEYWORDS: Hospital Waste Management; Solid Waste Generation; Per-Bed-Day Waste; Environmental Performance; Healthcare Sustainability; Super Specialty Hospital.

1. INTRODUCTION

The healthcare facilities are highly resource-intensive settings that produce large amounts of solid waste and, at the same time, demand constant availability of safe drinking water. With the growth in size, specialty, and super specialty hospitals, the environmental footprint also grows, which increases the level of operational pressure needed by waste management and water supply systems. It is thus an essential part of the environment to be well governed, not only in protecting the environment but also in assuring patient safety, occupational hygiene, as well as adherence to regulations. Nevertheless, in fast-developing cities of low and middle-income countries (LMICs), the healthcare infrastructure, in many cases, fails to meet the increased service demand, leading to the occurrence of operational inefficiencies and continuous environmental hazards (Galhotra et al., 2023; Datta et al., 2018).

The management of hospital wastes remains an issue of concern on a global scale, mostly because of the heterogeneity of healthcare wastes and the risks that they may spread infectious diseases, poisonous chemicals, or pollutants in the environment. Research shows that segregation in practices, lack of staff education, and ad hoc compliance with biomedical waste regulations is common in most medical institutions, especially in developing nations (Datta et al., 2018; Shastry and Rao, 2020). Industry analysis also shows that the rise in the use of single-use medical materials, pharmaceutical products, and packaging only continues to add to the amount of waste, which makes it a more significant burden on waste logistics, warehouses, and treatment systems (Daniels Health, 2024). This tendency is particularly noticeable in large-volume institutions in India, where the turnover of patients is high, and the pressure of operational processes on the environmental system is equally high.

This is important due to the fact that the quality of water is directly related to patient care, sterilization, food service, sanitation, and infection control, and thus it is essential to ensure the availability of reliable and safe drinking water in hospitals. Although central, a large number of study findings indicate systemic vulnerabilities in hospital water systems that include water treatment deficiency as well as distribution pipelines and storage tanks contamination (Hassan et al., 2025; Mian et al., 2021). The studies of Indian healthcare establish a constant lack of WASH (Water, Sanitation, and Hygiene) infrastructure, such as inconsistent supply, natural deterioration, and insufficient monitoring, leading to an increased risk of healthcare-associated infections (Galhotra et al., 2023; Odjegba et al., 2024). The quality of water that comes out of the treatment process can also rapidly decline between the treatment point and the point of use, which can result in biomass growth, sometimes caused by infrastructural failures, or insufficient levels of residual chlorine, which is of particular concern in hospitals that receive and keep immunocompromised patients.

Regardless of these thoroughly documented issues, the available studies usually study the waste management or water quality separately. Not many studies are aimed at examining the two areas in one hospital environment, even though such systems are functionally interrelated due to sterilization procedures, sanitation operations, and environmental hygiene protocols. The waste and water systems approach would offer a more comprehensive assessment of hospital environmental performance and reveal cross-cutting weaknesses that, when independently studied, might not be noticeable (Bigoni et al., 2014; WHO, 2024). In addition, the incorporation of these evaluations supports the new trends in sustainability models that call on healthcare institutions to implement total environmental monitoring strategies as opposed to disjointed interventions.

Although past research deals with biomedical waste or water quality separately, it is said that little has been done to evaluate both systems together in a super specialty hospital. The interrelation between waste management and water safety makes the difference in infection control, although it is not widely studied.

This study aims to evaluate the performance and temporal trends of waste generation and segregation in a super specialty hospital, assess the quality, reliability of distribution, and regulatory compliance of the drinking water supply system, identify key operational challenges affecting environmental sustainability, and propose evidence-based recommendations to strengthen hospital environmental management systems.

2. LITERATURE REVIEW

Daniels Health (2024) underlines the increasing role of organized and effective waste management in hospitals as medical institutions become larger, more complex, and their population increases. The report describes the risks of inappropriate management of general and biomedical waste to result in serious operational and health risks to the population, such as spreading infection, polluting the environment, and presenting a workplace risk to healthcare providers. It also claims that the conventional waste disposal methods are becoming unsuitable in the current hospital environment, whereby there is a high turnover of disposable items, including medical consumables and food service items has resulting in large volumes of waste that need careful segregation and tracking. Daniels Health emphasizes the necessity of integrated waste management systems that would be accompanied by the training of the staff, the use of safety-engineered containers, the optimization of the workflows, and the presence of continuous monitoring mechanisms. The paper has emphasized that sustainable waste management not only helps in reducing risks but also helps in regulatory compliance, cost-efficiency, and improved reputation of the institutions. The presented insights present a viable policy on how to perceive the operational issues that modern hospitals face and how these issues may be addressed with the help of the strategies that boost the governance of waste.

Datta et al. (2018) give a critical analysis of biomedical waste management in the Indian health care system, and it has been found that there are still loopholes between specifications and the real practice. Their evaluation finds some systemic issues, such as the lack of source segregation, poor disposal methods, a lack of personal protective equipment, and inadequate staff knowledge about the biomedical waste regulations. The authors underscore the fact that although established regulatory frameworks are in place, compliance rates are low because of the infrastructural constraints, lack of proper monitoring, and the disparity in the availability of resources in different institutions. The paper underlines the fact that not only is the environmental safety endangered by the ineffective waste management practices, but the direct health hazards associated with this practice are also posed by the healthcare workers and the communities around them.

Galhotra et al. (2023) presents a situational analysis of water, sanitation, and hygiene (WASH) infrastructure in Indian healthcare institutions, shedding light on the critical gaps, which directly affect the level of environmental safety, infection control, and overall quality of healthcare. In their research, they find that most institutions are faced with poor access to safe drinking water, intermittent sanitation facilities, and low waste management facilities. These infrastructural shortages are further worsened by a lack of proper systems to maintain them, a lack of proper staff training, and a lack of mechanisms for monitoring adherence to national WASH guidelines. The authors suggest that inadequate WASH infrastructure compromises patient safety and fosters the development of healthcare-associated infections, especially in resource-limited environments, where the number of patients is large. Notably, the research highlights the necessity of combined policy enforcement, long-term investment in infrastructural projects, and a consistent assessment to enhance the WASH indicators in healthcare facilities.

Hassan et al. (2025) provide a detailed assessment of drinking water quality and distribution network performance in Madinah City, Saudi Arabia, with valuable information regarding the interplay between the process of water treatment, distribution system, and the safety of water consumed by the end-users. The research points out that the quality of water at the point-of-use may be reduced because of the ageing distribution pipelines, contamination of storage tanks, and variable levels of residual chlorine, although the municipal water treatment process may be improved. Their results show that there is a considerable spatial variability of physicochemical and microbiological parameters, indicating that the integrity of the distribution network is a determinant of the quality of drinking water in institutions, such as healthcare facilities. The authors promote regular monitoring of water quality, the restoration of infrastructure, and the optimization of chlorination as the necessary measures to ensure that the water consumers can enjoy safe drinking. This study is especially relevant to drinking water tests in hospitals since it demonstrates that the systemic weaknesses in the distribution systems, rather than the quality of the source water, can provide an opportunity to challenge the quality of patient safety and the efficiency of operations and infection control.

Joshi et al. (2015) deliver significant qualitative data about how healthcare employees perceive and practice biomedical waste management at a rural tertiary care hospital in India. Their analysis demonstrates that there is a significant difference in staff awareness, attitudes, and adherence to the laid-down guidelines, and they indicate the importance of human behavior in determining the efficiency of the waste management system. The authors discovered that, in spite of the fact that a part of the personnel was well-informed about the process of segregation and the rules, a great number of them were not regularly trained and showed little awareness of the dangers of improper handling of waste. Pressures in the workload, resource limitations, and poor institutional controls were also among the factors that led to breaches of safe waste practices. The paper stresses that quality waste management in biomedical industries is not just a matter of infrastructure and regulations, but it must be ongoing capacity building, overseeing, and enforcement of best practices at all levels of the healthcare personnel.

3. MATERIALS AND METHODS

3.1. Study Site

The research was conducted at one of the largest tertiary-care and referral hospitals in the region, with a bed capacity of 1,300 patients in a super specialty teaching hospital situated in South India. The hospital is an integrated medical complex that combines clinical services, academic teaching, and translational research, and serves an average of 8,000-10,000 outpatients every day, and a maintained bed occupancy rate of more than 85%. Its geographical position in a highly populated district and the fact that it is considered a referral hospital for high-acuity cases in the surrounding states make it a high demand for environmental support systems, such as waste management and the provision of potable water.

The hospital has over 30 specialty divisions, which include cardiology, cardiovascular and thoracic surgery, oncology, neurology, nephrology, gastroenterology, trauma care, maternal and child health, surgical super specialties, and organ transplantation units. These intensive departments produce complicated waste streams which consist of food and general solid, consumable packaging waste, sharps, infectious waste, laboratory by-products, and pharmaceutical waste. The heterogeneity and the magnitude of clinical operations in the facility make it a representative area of research in examining the dynamics of waste generation and the performance of environmental management in big hospital systems in India.

In terms of infrastructure, the hospital operates several critical support units relevant to this study:

- Central Waste Collection and Segregation Areas, equipped for temporary storage of general waste, biomedical waste (BMW), and recyclable materials.
- A Biomedical Waste Treatment Facility (outsourced) adhering to Biomedical Waste Management Rules, 2016, which handles off-site treatment through incineration, autoclaving, and shredding.
- A multi-tier drinking water distribution network, consisting of:
  - Raw water intake from municipal and borewell sources
  - Pre-treatment and filtration units
  - Reverse Osmosis (RO) plants for potable water
  - A system of underground and overhead storage tanks
  - Extensive distribution pipelines supplying wards, ICUs, operating theatres, laboratories, and public areas

The water consumption in the hospital is high and daily, as it is necessitated by the need to carry out clinical operations, disinfection, laundry, sterilization, food services, and sanitation. A fluctuating water consumption and quality between seasons and service areas is common to large health systems as a problem in its operations.

The chosen hospital is an excellent example of the study since it presents a range of waste streams, various water infrastructure, and is of a sufficient scale to observe the effectiveness, state of compliance, and weaknesses in the operation of environmental sustainability systems. Its appropriateness as an empirical study location in which to conduct high-impact research aimed at investigating healthcare environmental management under low- and middle-income conditions is further reinforced by the abundance of multi-year waste data and seasonal water quality data.

3.2. Data Sources

3.2.1. General Waste Datasets (2022–2024)

The hospital Environmental Services Department provided general waste datasets that included those done between the months of January 2022 and December 2024. These records were used to record the amounts of solid non-hazardous waste produced each day in the entire facility, and these amounts were added up with a calibrated weight measurement in the central collection point. The datasets contained full date-based records, which allowed longitudinal evaluation of the waste generation trends, seasonal changes, and the performance trends per annum. The unit-level information was included in the dataset in several months, which helped to compare it between the clinical and non-clinical departments. These records were increased in reliability by regularly reconciling them with internal logbooks and the disposal manifests that the authorized waste-handling agency issues. Together, these sets of waste data gave the empirical basis on which the generation indices of waste, year-on-year changes, and operational efficiency of the waste management system could be measured in the hospital.

3.3. Analytical Methods

The research also used a mixture of quantitative, comparative, and compliance-based analysis methods to assess the effectiveness of the hospital in terms of waste management and drinking water distribution systems. The analytical framework was geared towards providing methodological strength, triangulation of the results, and congruence with the standard procedures of environmental health assessment.

In the part waste management, descriptive statistical data analysis was done on the daily waste generation data in the current year 2022-2024, and central tendency, dispersion, and general variability were calculated. Standard deviations, inter-annual percentage changes, and mean daily values were computed to determine the pattern and variation in time related to the changes in patient load, level of clinical activity, or seasonal effects. To create an index of waste generated per-bed-day, the daily waste quantities were normalized using the functional bed capacity and the average occupancy rates of the hospital; this index allowed the comparison with the national and international standards, such as the WHO norms of waste generation in large healthcare institutions. The visualizations were created using time series, which helped to visualize the transitions between the years and show possible anomalies. Comparisons across units of the hospital were conducted where necessary to determine variation in the intensity of waste and to identify operational inefficiencies.

Cleaning and validation of data were used in the process of analysis. The discrepancies or omissions of the waste data were handled with references to the departmental records or with the conservative methods of imputation, whereas the results of water quality tests were checked with the criteria of laboratory credibility and consistency of the methodology. With the help of quantitative measures and qualitative contextual knowledge, the analytical approach provided the opportunity to fully assess performance and to find out what systemic issues should be approached at the operational or policy level.

4. RESULTS

This part is the empirical result of the cleaned multi-year data of waste generation (20222024) and the monthly trends comparison. The outcomes are indicative of the operational efficiency of the solid waste system of the hospital and form a reference point for assessing the efficiency of the system with respect to the environment. Any analysis will be done on the clean dataset that has been generated after the systematic data cleaning, date normalization, outlier elimination and aggregation processes.

4.1. Data Cleaning and Validation Outcomes

To increase the reliability of the three annual datasets, a systematic validation protocol was used to improve the quality of all records, as well as to ensure that the following analysis was conducted using high-quality, internally consistent records. The cleaning procedure was conducted, and the results are provided in Table 4.1. Each year, the raw data were checked against duplicate records, invalid numerical data (negative or zero quantities), and implausibly high outliers, as well as discrepancies in date format.

Table 4.1: Cleaning Report for Waste Datasets (2022–2024).

Year	Original Rows	Cleaned Rows (Daily Records)	% Removed
2022	365	365	0.00%
2023	365	365	0.00%
2024	366	366	0.00%

The findings reveal that the three sets of data had very high levels of baseline integrity, and none of the data sets had to be dropped once outlier screening and data-parsing were performed. Thus, the entirety of the initial daily records of 2022, 2023, and 2024 was stored to be analyzed. Such a level of data completeness shows that the Environmental Services Department of the hospital has strong internal documentation controls and minimizes the fears of measurement error or reporting gaps.

By holding the entire dataset in all the years, this adds to the validity of the trend analysis carried out later on and gives assurance that the patterns of trends that are observed (i.e., inter-annual growth in waste generation) are not due to the data quality problems at hand.

4.2. Annual Waste Generation Trends (2022–2024)

The waste records at the end of the day in the 3 years had a steady increase in the overall waste generated. The cleaned data, comprising the daily waste quantities, the annual amounts, standard deviations, and the per-bed-day waste index, are summarized in Table 4.2 using the operational capacity of the facility of 1,300 beds.

Table 4.2: Summary of Cleaned Daily Waste Generation (2022–2024).

Year	Mean Daily Waste (kg/day)	Std. Dev (kg)	Total Annual Waste (kg)	Per-Bed-Day Waste (kg)	Days Recorded
2022	365.13	91.51	133,376	0.2811	365
2023	373.45	91.18	136,308	0.2873	365
2024	393.90	120.92	144,168	0.3030	366

The values of the cleaned data show that there is a clear and consistent increasing trend in the amount of waste produced during the three years. The total annual waste production rose by almost 8% with the total amount of waste generated in 2022 of 133,376 kg and 144,168 kg in 2024, respectively. This is a growth that is consistent with the wider institutional development and increased operational need. On the same note, the index of waste in terms of the number of beds/day also showed improvement year-to-year, with 2022 at 0.281 kg/bed/day and 2023 at 0.287kg/bed/day, and 2024 at 0.303 kg/bed/day. The positive change in this measure indicates the growth in the turnover of patients, growth in clinical services, and possible inefficiencies in material use and disposal procedures at the hospital. Also, in 2024, the standard deviation of daily waste products grew significantly, to 120.92 kg, suggesting the higher variability of waste generation and significant fluctuations in the quantity of waste generated daily. This irregularity will probably be linked to times of increased clinical activity, surges in inpatient admissions, or even episodic occurrences that increase operational workloads, temporarily.

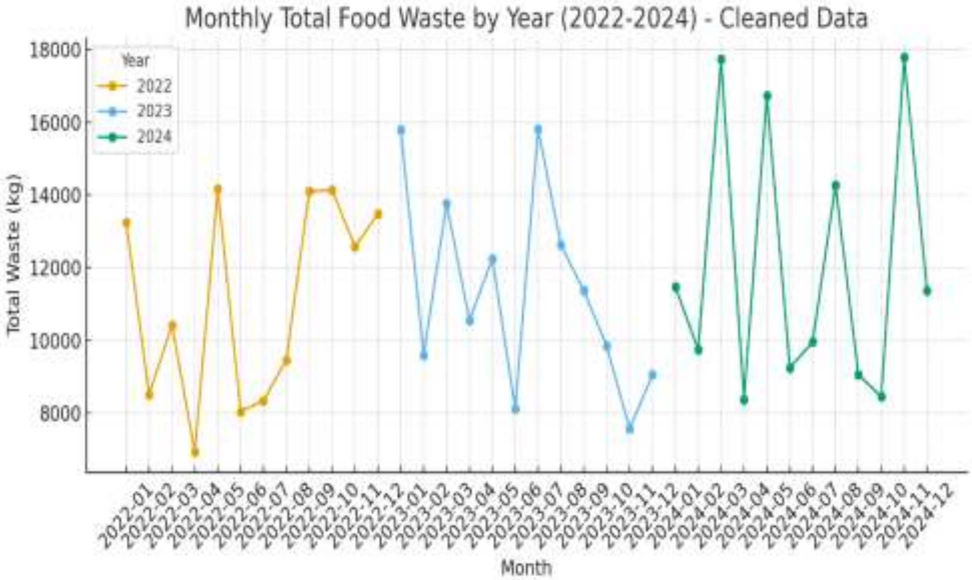

Figure 4.1: Monthly Total Waste Generation for 2022–2024

This figure shows the sum of the monthly solid waste amounts of the years 2022, 2023, and 2024 after data normalisation and purification. The figure shows that there is an apparent inter-annual growth in waste production, with the highest monthly amounts constantly being registered in 2024. The clinical activity is high in all the years, with high peaks of all seasons being the mid-monsoon and post-monsoon months. The cleaned data eliminates the outliers and inconsistencies, hence giving a sound depiction of the trends in operational wastes.

3.3. Monthly Waste Generation Patterns

A month-by-month summation of the cleaned daily waste data will give more understanding on the variables of time variation and seasonal operation patterns within the hospital. Table 4.3 demonstrates that the generation of waste has a steady seasonal fluctuation throughout the three years of study (2022–2024). These trends indicate the cyclical nature of clinical loads and patient turnover of the hospital, as well as the fluctuation of intensity of procedures and support services.

Peaks of waste are to be expected during certain months when diseases reach their highest levels due to monsoon and post-monsoon related diseases, and when there is an upsurge in elective medical activity levels. On the other hand, the months at the start of every year tend to show lower numbers, which represent a cut in the elective procedures and decreased attendance of outpatients. These repeatable seasonal patterns over years point to the predictability of the waste production patterns in large tertiary hospitals and have significant consequences to resource planning, staffing, and management of waste logistics.

Table 4.3: Monthly Total Waste (Kg) For 2022–2024 (Cleaned Dataset).

Month	2022 (kg)	2023 (kg)	2024 (kg)
January	11,564	10,719	11,967
February	10,660	10,714	10,515
March	11,185	12,337	15,756
April	10,423	10,352	9,661
May	10,398	11,794	14,390
June	9,937	10,503	10,160
July	11,332	11,220	10,529
August	10,772	10,552	13,744
September	10,671	11,327	10,417
October	10,780	10,729	9,763
November	9,279	9,023	15,285
December	11,375	9,712	11,981

One of the interesting conclusions is that the amount of waste increased significantly in 2024, as almost every month demonstrates the generation of more waste than in the same months of 2022 and 2023. The extreme peaks are the number of March (15,756 kg) and November (15,285 kg) in 2024. The increases can be indicated by an increase in clinical services, an increase in patient throughput, or the operational changes that increased material consumption, such as consumables and food services. These annual increases point to the necessity to see the capacity to handle the waste and the efficiency measures on the capacity increase to ensure the environmental management system will not be overstrained.

Table 4.3 shows a temporal distribution of waste generation, which indicates that the generation of waste followed specific and recurring patterns in the three study years that are seasonal. The amount of waste always increases during June to August, which are known as monsoon months, as well as during the post-monsoon months of October and November. These seasonal peaks are in line with clinical activity that is usually high, which is usually accompanied by infectious diseases and other diseases carried by vectors, which are on the increase during these months, leading to higher patient admissions. The intensifying diagnostic and therapeutic processes during these periods, as well as the increased consumption of support services, including food preparation, linens, and disposable medical supplies, are some of the contributory factors to the witnessed increase in the generation of waste. Besides these seasonal trends, the figures indicate a definite increase in inter-annual waste production, as 2024 has witnessed higher numbers in the monthly waste than in 2022 and 2023 in most months. This consistent increasing pattern represents the institutional growth in general, such as the growth of clinical services, the growth of procedural throughput, and the overall inflow of patients. This escalation in operations inevitably intensifies the generation of waste and contributes to the necessity of a commensurate increase in the capacity of waste management.

In 2024, the variation is very high, with two months (March and November) showing very high waste amounts, which implies that there are bursts of waste that are beyond the normal seasonal changes. The causes of such spikes can be the institution-wide clinical projects (e.g., health camps, the focused times of a large surgery schedule, outbreak of a seasonal disease, etc.), which cause the momentary measure of the pressure on the hospital services. These unusual peaks impose further pressure on the waste collection, transportation, and storage system, which is an indicator of the importance of having flexible and resilient waste management procedures that have the capacity to absorb the unexpected operational pressures.

4.5. Per-Bed-Day Waste Analysis

Per-bed-day waste production provides a normalized measure of how effectively a waste management system in a hospital is operating, especially where the number of patients and the intensity of services fluctuate considerably over time in a tertiary-care setting. Division of mean quantities of waste generated per day by the functional capacity of the hospital in terms of the number of beds gives a tuned measure of material throughput in relation to the service provision. The three-year cleaned data analysis shows that there is a slow yet steady rise in the amount of waste generated per-bed-day, with an increase in the value of 0.281kg/bed/day in 2022 to 0.287kg/bed/day in 2023, and finally 0.303kg/bed/day in 2024. Though the values are still in the acceptable range documented in similar healthcare facilities, the trend is on the positive side to indicate the growing institutional activities, patient turnover, and dependence on disposable medical and support products.

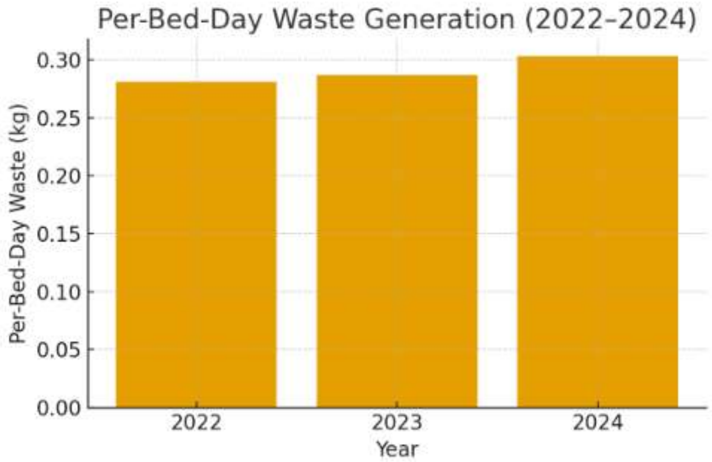

Figure 2: Per-Bed-Day Waste Generation Trend (2022–2024).

The per-bed-day trend of waste is Figure 2, which visualizes the trend of waste over the period of the study. The figure is a good demonstration of the year-by-year increase, which supports the quantitative results and emphasizes the fact that the operations of the hospital become more and more aggressive. This visualization gives a brief history of the increasing quality of waste generation based on the service capacity and can be used as a crucial point of reference in further planning of waste-handling facilities.

4. DISCUSSION

The paper illustrates that the environmental infrastructure in super specialty hospitals has a complex nature because of scale, resource intensity, and dynamic patient load. The production of waste surpassed WHO standards and went up every year, which indicated the presence of inefficiency in the management of materials, food service processes, and housekeeping. Enhancing the segregation is important in decreasing the downstream environmental burden and treatment expenditure.

Though the quality of the water consumed was within BIS requirements of pH and TDS, as well as turbidity, intermittent microbial positivity is an important safety issue. This is consistent with the results of other Indian tertiary hospitals, which reported that infrastructural age and poor maintenance of tanks were the main factors that undermined the microbial safety (Saji et al., 2020).

Implementation of environmental management will involve coordinated planning between the water department, waste department, infection control department as well as the engineering department. Sustainability requires data-driven surveillance, digital tracking systems, and accountability systems.

The results of the current research are integrative in their comprehension of waste generation dynamics in a large super specialty hospital and demonstrate several structural, operational, and environmental factors that affect the production of waste over three years. The Trend of the annual, monthly, and per-bed-day waste indices indicates that the facility is experiencing a continuous growth in clinical and support services, and the result was that more material throughput was attained in various areas of operation. These tendencies can be explained by the trends in similar tertiary health systems in the rapidly developing areas, as increasing patient volumes and the spread of sophisticated diagnostics and surgical procedures add up to significant amounts of solid waste. The overall growth in the amount of waste (133,376 kg in 2022, up to 144,168 kg in 2024) is a part of the institutional growth and deepening of healthcare operations. This increase in the daily volume of waste by almost 8 percent highlights the exponential nature of the growing inpatient turnover, increased capacity of the procedures, and increased use of single-use consumables in the process. It is interesting to note that this increase in waste was irrespective of the non-occurrence of anomalies, data inconsistencies, validated by the process of having undergone a thorough dataset cleaning and verification. The credibility of the background data promotes a sense of reliability in the trends being observed and furthermore makes sure that the projection of time activities is much more precise and that the operations can be seen as they are and not as a result of reporting procedures.

Seasonal variation was a constant trend, as an increase in the waste levels was observed during monsoon and post-monsoon months in all three years. Such peaks can be explained by well-known epidemiological cycles which increase hospitalizations in the infectious, respiratory, gastrointestinal, and vector-borne diseases within this time interval. Higher volumes of diagnostic investigations, therapeutic interventions, as well as patient support functions such as food services and housekeeping, among others, will all add to high volumes of waste. These recurring seasonal cycles imply some form of predictability that hospital administrators can use to make advanced planning, such as scaling the waste logistics, staffing optimization, and scheduling procurement operations. Major spikes in waste levels in March of 2024 and November of 2024 are especially worth noting since they are not observed in terms of monthly averages and are more than what is typically expected in terms of seasonal variations. These variances can be related to temporary increases in operational levels, like specialty surgical camps or increased outpatient programs, or temporary outbreaks of infections. Their presence emphasizes the importance of resilience in the waste management systems so that temporary increases will not cover the storage, transport, or treatment capacity. Hospitals that run their business environment where demands are high are thus required to establish flexible waste-handling systems that can absorb spikes of demand without undermining the Biomedical Waste Management Rules and the safety of operation.

The per-bed-day analysis supports the evidence of intensification of the process of waste generation in comparison with the service capacity. Despite the fact that the per-bed-day values were within the international standards, the increased amount of 0.281kg/bed/day in 2022 to 0.303kg/bed/day in 2024 shows that the material consumption per patient is on the increase. The findings are similar to the world issues of resource efficiency in healthcare because the increasing use of disposable products, aided by the demands of infection control, convenience in practices, and patient demands, creates sustainability challenges. The per-bed-day trends visualization clearly shows that the trend of upward gradient is steady, which means that some strategic interventions to reduce waste, procure responsibly, and manage materials responsibly are required.

Combined, the findings prove that the patterns of waste generation at the institution are predictable both in seasonal and annual cycles; the size of the waste generation is on the rise and therefore needs to be planned proactively. The environmental management system of the hospital needs to adapt to these operational realities through introducing data-driven forecasting, investing in scalable waste infrastructure, and promoting behavior change in clinical and non-clinical staff. These are necessary to comply and be environmental custodians, but also to ensure efficiency in operations in light of the growing service needs.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The proposed study offers an in-depth analysis of waste production trends and operational efficiency of a large, South Indian-based super specialty teaching hospital in three years (2022-2024). Combining the data cleaned on a multi-year basis, monthly trend analysis, per-bed-day waste, and visualization, the study provides insight into the environmental load of the hospital as well as its dynamics over time. The findings show that there has been a steady increase in the waste level, which is associated with the growth of clinical services that the institution offers, the number of patients that it attends to, and the complexity of the operations. Seasonal variations with monsoon-related and post-monsoon associated peaks are recurrent in all the years and indicate predictable changes associated with epidemiological oscillations. The spikes in waste taking place in March and November 2024 are important indicators of the impact of periodic surges in operational activity and the necessity of flexible waste management systems that could allow meeting the temporary rise in the amount of waste. The per-bed-day waste evaluation also proves the increasing waste intensity in relation to the service capacity, which is a reference to the increased material usage and possible inefficiency of the resource utilization.

Together, these results depict the fact that the environmental management system of the hospital functions under the gradually growing pressures and should develop in order to remain complying, safe, and sustainable. The accuracy of the datasets and evidence-based by strong cleaning and validation is the force behind the validity of these insights and the importance of data-driven methods in assessing hospital environmental performance.

5.2 Recommendations

According to the analysis, it is possible to come up with several specific recommendations that can be used to improve the system of waste management and make the hospital more sustainable. To begin with, it is necessary to implement data-driven waste monitoring systems. The introduction of digital dashboards and automated data-capture tools would enable the hospital to manage the waste generation in real time, thereby detecting any abnormalities early enough, plan to ensure the peak times, and enhance compliance with regulations. Second, one can put more emphasis on the enhancement of segregation practices and material-use efficiency. The enhancement of cross-contamination between general and biomedical waste streams may be achieved through stronger training of both clinical and non-clinical labor, and the reduction of the use of unnecessary materials may be achieved through the change of the procurement policies that will prioritize reusable or low-waste consumables. The hospital should increase the volume of its waste storage and transportation to meet the increase in volumes of waste. The inspection and scaling of the internal storage space, the rise of the number of bins, and the optimization of the transportation times will make sure that the waste will be delivered to sorting zones in a timely and secure manner. They should also design seasonal and surge-responsive working procedures, especially to meet forecasted monsoon-related rise in patient admissions or intermittent surges of activity in the clinical service. These guidelines can include the temporary staffing changes, the introduction of additional containers, and the increased communication with waste treatment providers. Another important recommendation is to enhance staff awareness/accountability. Adherence to waste management standards can be reinforced by periodic workshops, visual aid, and incentive mechanisms, particularly in high-pressure units like the emergency unit, intensive care, and surgical units. On a policy level, institutional governance would be more appropriate by incorporating the sustainability aspects in order to make the aspects of environmental accountability institutional. The formation of a special Environmental Management Committee may assist with developing the long-term sustainability initiatives, such as waste reduction goals, green procurement methods, and circular-economy-related ones. Regular audits and benchmarking activities (annually or biannually) would give a continued understanding of the work of the system, the parts that need changes, and enhance the alignment of the hospital with the national and international best practices.

REFERENCES

Attrah, M., Elmanadely, A., Akter, D., & Rene, E. R. (2022). A review on medical waste management: Treatment, recycling, and disposal options. Environments, 9(11), 146. https://doi.org/10.3390/environments9110146

Bansod, H. S., & Deshpande, V. Y. (2023). Biomedical waste management and its importance. Journal of Environmental and Public Health, 2023, Article 9981497. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9981497/

Bigoni, R., Acosta-Jiménez, L., & Castelletti, A. (2014). Drinking water quality assessment and corrosion mitigation in the hospital water supply system of Chacas Village, Peru. Revista Ambiente & Água, 9(3), 1–12.

Central Pollution Control Board (CPCB). (2018). Guidelines for management of healthcare waste. Ministry of Environment, Forests and Climate Change, Government of India. https://cpcb.nic.in/uploads/projects/bio-medical-waste/guidelines_healthcare_june_2018.pdf

Daniels Health. (2024). Importance of hospital waste management. Daniels Health Knowledge Center. https://www.danielshealth.com/knowledge-center/hospital-waste-management

Datta, P., Mohi, G. K., & Chander, J. (2018). Biomedical waste management in India: Critical appraisal. Journal of Environmental and Public Health, 2018, Article 5784295. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5784295/

Galhotra, A., Galhotra, S., Sharma, A., & Dhingra, S. (2023). Situational analysis of WASH infrastructure in healthcare facilities in India. Journal of Public Health. https://pmc.ncbi.nlm.nih.gov/articles/PMC10789470/

Hassan, I., Salamah, S. K., & Bob, M. (2025). Comprehensive evaluation of drinking water quality and the effect of the distribution network in Madinah City, Saudi Arabia. Water, 17(18), 2711. https://doi.org/10.3390/w17182711

Joshi, S. C., Diwan, V., Tamhankar, A. J., Joshi, R., & Shah, H. (2015). Staff perception on biomedical or health care waste management: A qualitative study in a rural tertiary care hospital in India. PLOS ONE, 10(5), e0128383. https://doi.org/10.1371/journal.pone.0128383

Mian, H. R., Wang, Q., & Al-Juboori, R. (2021). Drinking water quality assessment in distribution networks: Frameworks and approaches. Science of the Total Environment, 780, 146555. https://www.sciencedirect.com/science/article/pii/S0048969721009116

Odjegba, E. E., Adeola, T., & Paul, B. (2024). Water, sanitation and hygiene (WASH) index for primary healthcare facilities. Science of the Total Environment, 874, 162244.

Shastry, C. S., & Rao, V. (2020). Water, sanitation, hygiene and biomedical waste disposal in the healthcare system: A review. Biomedicine, 40(1), 1–15.

World Health Organization. (2022). Guidelines for drinking-water quality (4th ed.). WHO Press. https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/water-safety-and-quality/drinking-water-quality-guidelines

World Health Organization. (2024). Health-care waste: Fact sheet. https://www.who.int/news-room/fact-sheets/detail/health-care-waste

Xalxo, S. M., & Paliwal, H. B. (2024). Evaluation of drinking water quality in hospitals: A study from Ranchi, Jharkhand, India. International Journal of Environment and Climate Change, 14(12), 133–139.