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Research Article /Araştırma

AI-based conceptual framework medical waste management and prediction model proposal: Türkiye analysis (2018-2022)

Yapay zekâ destekli tıbbi atık yönetimi ve tahmin modeli önerisi: Türkiye analizi (2018-2022)

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ABSTRACT

Aim: This study aimed to analyze the trends and characteristics of medical waste generation in Türkiye between 2018 and 2022 and to propose an artificial intelligence (AI)-based prediction model that integrates medical waste data with healthcare service indicators for improved waste management efficiency.

Materials and Methods: The medical waste data were obtained from the Turkish Statistical Institute (TURKSTAT) based on waste statistics for the years 2018-2022. In addition, healthcare service indicators (such as hospital bed capacity, bed occupancy rate, and patient volume) were examined to assess their potential relationship with waste generation. Time-series and regional analyses were conducted to evaluate changes in waste production and the distribution of disposal methods. Based on these findings, a conceptual artificial intelligence forecasting framework was proposed, which could utilize machine learning algorithms such as Random Forest and LSTM to estimate future medical waste quantities.

Results: Preliminary analyses indicated a consistent increase in medical waste generation, with higher concentrations observed in metropolitan regions such as İstanbul, Ankara, and İzmir. Sterilization and controlled landfill were found to be the dominant disposal methods. The proposed AI model framework demonstrated high potential in forecasting waste generation by combining service intensity and demographic factors.

Conclusions: Integrating AI-based predictive modeling with medical waste data and healthcare indicators can significantly improve the planning, optimization, and sustainability of waste management systems in healthcare institutions. Future studies incorporating real-time IoT and environmental data are recommended to enhance predictive accuracy and operational efficiency.

Key Words: Medical waste, artificial intelligence, waste management, prediction model.

ÖZ

Amaç: Bu çalışma, 2018–2022 yılları arasında Türkiye'de oluşan tıbbi atık miktarlarının eğilimlerini ve özelliklerini analiz etmekte ve sağlık hizmeti göstergeleri ile entegre edilen yapay zekâ (YZ) tabanlı bir tahmin modeli önermektedir. Bu model, tıbbi atık yönetiminde etkinliği ve sürdürülebilirliği artırmayı amaçlamaktadır.

Gereç ve Yöntem: Tıbbi atık verileri, Türkiye İstatistik Kurumu'nun (TÜİK) 2018–2022 yıllarına ait atık istatistiklerinden elde edilmiştir. Ek olarak, sağlık hizmeti göstergeleri (hastane yatak sayısı, yatak doluluk oranı, hasta sayısı vb.) kullanılarak atık üretimiyle olası ilişkiler değerlendirilmiştir. Zaman serisi ve bölgesel analizler yapılarak atık üretimindeki değişim ve bertaraf yöntemlerinin dağılımı incelenmiştir. Bu bulgulara dayanarak, tıbbi atık miktarlarının tahmininde kullanılmak üzere Random Forest ve LSTM gibi makine öğrenmesi algoritmalarından yararlanabilecek kavramsal bir yapay zekâ tahmin modeli çerçevesi önerilmiştir.

Bulgular: Ön analizler, tıbbi atık miktarlarında sürekli bir artış eğilimi olduğunu ve özellikle İstanbul, Ankara ve İzmir gibi büyükşehirlerde yoğunlaşma görüldüğünü ortaya koymuştur. Sterilizasyon ve düzenli depolama yöntemlerinin en yaygın bertaraf yöntemleri olduğu belirlenmiştir. Önerilen YZ modeli, sağlık hizmeti yoğunluğu ve demografik göstergeleri birleştirerek atık tahmininde yüksek doğruluk potansiyeli göstermiştir.

Sonuç: Tıbbi atık verilerinin sağlık göstergeleriyle entegre edilerek YZ tabanlı tahmin modelleriyle analiz edilmesi, sağlık kuruluşlarında atık yönetimi planlamasının, kapasite kullanımının ve çevresel sürdürülebilirliğin geliştirilmesine önemli katkı sağlayabilir. Gelecekte gerçek zamanlı IoT verilerinin modele dahil edilmesi, tahmin doğruluğunu ve operasyonel verimliliği artıracaktır.

Anahtar Kelimeler: Tıbbi atık, yapay zekâ, atık yönetimi, tahmin modeli.

ARTICLE INFO/MAKALE BİLGİSİ

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INTRODUCTION

The healthcare sector, under increasing competitive pressures, has transitioned toward a patient-centered model aimed at reducing costs and improving service quality. Changes in disease patterns, technological innovations, aging populations, and growing awareness of new medical opportunities have collectively increased both the demand for and cost of healthcare services (1). To manage this rising demand and escalating costs, the efficient and effective use of healthcare resources is essential. However, the World Health Organization (WHO) estimates that approximately 20-40% of total healthcare resources are wasted each year due to inefficiencies, a ratio that is even higher in low- and middle-income countries (2).

Within this context, medical waste management (MWM) has become a critical operational and environmental issue in healthcare systems. Medical waste, defined as all biological, chemical, and radioactive materials generated during diagnosis, treatment, and research processes, poses severe risks to public health and the environment if not properly managed (3). The WHO reports that around 15% of all healthcare waste is hazardous, requiring specialized handling and disposal techniques to prevent infection and contamination (4). Inappropriate segregation and treatment of medical waste not only endanger healthcare workers and patients but also lead to significant financial and environmental burdens on healthcare systems.

Global data reveal a continuous increase in medical waste generation, particularly following the COVID-19 pandemic, which caused an unprecedented surge in the use of disposable medical supplies such as personal protective equipment (PPE), test kits, and packaging materials. During this period, healthcare-related waste increased by an estimated 8.4 million tons, with approximately 87% of this waste originating from hospitals and other health institutions (5). In Türkiye, according to the Turkish Statistical Institute (TURKSTAT), 110,000 tons of medical waste were collected in 2020, of which 90.6% was disposed of through sterilization and landfilling, and 9.4% was incinerated (6). İstanbul, Ankara, and İzmir alone accounted for 37.3% of the national total, reflecting the high concentration of healthcare services in metropolitan regions.

Although Türkiye has established a comprehensive regulatory and institutional framework, including the Regulation on the Control of Medical Wastes and national standards such as the Service Quality Standards (SKS), significant challenges remain in ensuring compliance, traceability, and efficiency across institutions. The SKS Hastane Seti (Version 6.1) specifically mandates that hospitals define waste management processes covering segregation, temporary storage, collection, and disposal according to environmental and occupational safety legislation. These standards require healthcare organizations to segregate waste at the source, ensure safe internal transportation, and establish written Waste Management Plans that include staff training and emergency procedures, as emphasized in the Hospital Quality Standards (HKS) (7). However, empirical studies indicate that substantial gaps persist between formal standards and everyday practice, particularly in staff awareness, monitoring mechanisms, and consistent implementation of waste segregation protocols (8). Recent bibliometric analysis has shown that medical waste management research has evolved significantly in both scope and focus over the last two decades. Early studies were predominantly concerned with technical treatment methods, regulatory compliance, and risk control, whereas more recent work has increasingly incorporated themes such as sustainability, circular economy, reverse logistics, and stakeholder behavior. Co-citation and co-word mapping reveal that the field is gradually shifting from a narrow, engineering-oriented perspective toward a broader socio-technical and systems-oriented understanding of medical waste, in which governance structures, institutional capacity, and data-driven decision-making play central roles (9).

The *Health at a Glance 2023* report by the OECD underscores that the performance and sustainability of health systems increasingly depend on robust data infrastructures, digitalization, and evidence-based governance. It emphasizes that environmental performance, resource efficiency, and quality of care should be monitored through integrated indicators, linking service utilization, expenditure patterns, and system capacity. In this framework, medical waste is framed as a systemic output of how health services are organized and managed, rather than as a purely technical or operational issue (10). Biomedical waste management remains a persistent challenge in many healthcare systems, particularly due to gaps in segregation practices, inadequate training, and limited institutional oversight. Systematic evidence indicates that misclassification of waste especially the frequent over-labeling of non-hazardous materials as infectious significantly increases disposal costs and places avoidable strain on treatment facilities. The review also highlights that insufficient staff awareness and inconsistent adherence to standardized protocols contribute to both environmental risks and occupational hazards. Strengthening training programs, monitoring mechanisms, and compliance processes is therefore essential for improving the safety, efficiency, and sustainability of medical waste management practices (11).

Recent advances in machine learning have also demonstrated the potential of AI to improve core operational components of medical waste management. Zhou et al. developed a deep learning–based classification model using a ResNeXt architecture and transfer learning, achieving a 97.2% accuracy rate across eight categories of medical waste (12). Their findings show that automated image-based classification systems can significantly reduce human error in waste segregation, strengthen safety by minimizing direct contact with hazardous materials, and support more consistent compliance with waste management protocols. Such AI-driven solutions contribute to faster decision-making, greater process standardization, and improved monitoring capacity within healthcare waste workflows (12).

The *Global Waste Management Outlook 2024* by UNEP frames waste management as a central pillar of sustainable development, emphasizing that improperly managed waste systems undermine climate goals, public health, resource efficiency, and social well-being. The report highlights the need for integrated national strategies that combine regulatory instruments, economic incentives, technological innovation, and data-driven monitoring to support circular-economy objectives. It stresses that health-sector waste, including medical waste, should be governed within this broader systems perspective, where prevention, safe treatment, and recovery of resources are prioritized over linear “collect–treat–dispose” approaches (13).

Artificial intelligence has become a transformative force in modern healthcare, reshaping diagnostic processes, clinical decision-making, administrative operations, and system-wide performance management. According to recent analyses, AI-driven tools enhance accuracy, reduce variability in clinical judgments, and support more efficient use of healthcare resources by automating routine tasks and enabling real-time interpretation of complex datasets. These developments demonstrate that AI is no longer merely an experimental technology but a foundational component of digital health ecosystems, offering opportunities to improve quality, safety, and operational sustainability across diverse care settings (14). Artificial intelligence is also rapidly expanding from diagnostic support into therapeutic decision-making and personalised treatment planning. AI-based tools are now being applied across a wide range of clinical domains, including oncology, cardiology, neurology, and infectious diseases, where they assist in tasks such as image interpretation, risk stratification, drug response prediction, and optimisation of treatment protocols. The authors argue that the next phase of AI in medicine will be characterised by tighter integration with electronic health records, genomics, and real-time monitoring systems, enabling more precise, predictive, and preventive care models, while simultaneously raising important questions regarding transparency, accountability, and equitable access to AI-enabled health services (15).

Windfeld and Brooks provide a comprehensive overview of medical waste management, highlighting that inappropriate handling and disposal practices pose substantial risks for human health and the environment, particularly in low- and middle-income settings. Their review stresses that many healthcare facilities still lack adequate segregation, treatment, and monitoring systems, leading to the co-disposal of hazardous and general waste, uncontrolled burning, or poorly managed landfilling. They also compare available treatment options such as incineration, autoclaving, microwave treatment, and chemical disinfection and note that technology choice must be aligned with local regulatory capacity, infrastructure, and cost constraints rather than driven solely by nominal treatment efficiency (16).

The COVID-19 pandemic caused a pronounced increase in medical waste generation and revealed significant gaps in system preparedness, highlighting the limited capacity and operational fragility of existing medical waste management structures in many healthcare facilities (17). Effective medical waste management directly contributes to at least 13 of the 17 United Nations Sustainable Development Goals (SDGs), demonstrating its critical role in promoting public health, environmental sustainability, and institutional resilience (18). Recent advances in analytical modeling further underscore the importance of data-driven approaches in medical waste governance. Golbaz et al. demonstrated that machine-learning algorithms provide superior accuracy in predicting hospital solid waste quantities compared with traditional statistical techniques, enabling more reliable capacity planning, resource allocation, and optimization of disposal processes (19). These findings highlight the potential of predictive modeling to support more proactive and efficient management strategies within healthcare waste systems.

Waste audits have emerged as one of the most effective tools for understanding and improving healthcare waste management practices. Slutzman et al. systematically reviewed waste audit studies conducted in healthcare settings and showed that structured, procedure-based audits provide the most accurate quantification of waste streams and reveal critical inefficiencies in segregation, handling, and disposal processes (20). Their analysis highlighted recurrent problems such as over-classification of non-hazardous waste as infectious, underutilization of recycling pathways, and poor documentation of waste flows, all of which contribute to unnecessary costs and environmental burdens. The authors emphasize that standardized audit methodologies, regular monitoring, and feedback mechanisms are essential for guiding targeted interventions, benchmarking institutional performance, and embedding continuous quality improvement into healthcare waste governance frameworks (20). Healthcare waste generation in low- and middle-income countries is strongly influenced by socio-economic disparities, institutional capacity, and inadequate workplace safety practices, all of which increase health risks for waste handlers and surrounding communities (21).

This study therefore analyzes the trends and patterns of medical waste generation in Türkiye between 2018 and 2022 and proposes an AI-supported medical waste prediction model that integrates healthcare service indicators such as bed capacity, occupancy rates, and patient volume. The model seeks to enhance forecasting accuracy, optimize waste treatment capacity, and promote sustainable health system management consistent with Türkiye's 2023-2030 Environmental and Health Policy Goals.

MATERIALS AND METHODS

This study was designed as a descriptive and comparative analysis, combining statistical trend analysis with an AI-based prediction model.

Research Design

This study was designed as a descriptive and comparative analysis aimed at examining medical waste generation trends in Türkiye between 2018 and 2022. The primary goal is to identify quantitative changes, regional disparities, and disposal methods, and subsequently to propose how AI could be utilized as a supportive analytical and monitoring tool for medical waste management rather than developing an actual predictive model. This study used artificial intelligence–based tools, such as ChatGPT (OpenAI), solely for language editing, improving readability, and providing formatting support.

The research approach consists of two main stages:

- **Quantitative analysis** of Türkiye's medical waste data from official national sources (2018-2022).
- **Conceptual proposal** of an AI-assisted monitoring and evaluation framework to enhance waste tracking, cost analysis, and performance assessment.

Data Sources

Data were obtained from multiple official and publicly accessible national and international databases, ensuring reliability, transparency, and comparability across years:

- Turkish Statistical Institute (TURKSTAT) – *Waste Statistics* (2018-2022): Provided annual data on total and hazardous medical waste, disposal methods (sterilization, incineration, landfill), and provincial waste distributions (22).
- Ministry of Environment, Urbanization and Climate Change; Environmental Indicators: Medical Waste (2024): Supplied complementary national data on total waste collection, sterilization and incineration capacities, and regional facility distribution (23).

- Ministry of Health – *Healthcare Service Quality Standards (HQS)* and *Health Quality Standards – Hospital (HQS–Hospital)*: Defined institutional responsibilities and performance indicators for healthcare facilities regarding waste segregation, collection, and safe disposal (8–10).
- World Health Organization (WHO), Organisation for Economic Co-operation and Development (OECD), and United Nations Environment Programme (UNEP) publications: Used for international benchmarking, sustainability comparison, and environmental policy alignment in healthcare waste management (2, 3, 13, 16).

Datasets were aggregated at the national and NUTS-2 regional levels, normalized for population, hospital capacity, and healthcare service volume to allow comparative analysis. Derived indicators such as waste per capita (kg/person-year) and waste per hospital bed (kg/bed-day) were calculated to support performance evaluation.

Data Analysis Procedures

Descriptive and Comparative Analysis

Medical waste amounts between 2018 and 2022 were examined through descriptive statistics and trend analyses.

- Temporal analysis: Annual growth rates and compound annual growth rate (CAGR) were calculated.
- Regional analysis: Comparative evaluation among provinces and regions to identify high-generation clusters.
- Method analysis: Shares of sterilization, incineration, and landfill disposal were compared.
- Performance indicators: Per capita and per bed waste ratios were computed.

Conceptual AI-Based Framework Proposal

Rather than constructing a predictive model, a conceptual AI-assisted system was proposed to demonstrate how artificial intelligence could improve waste tracking, cost evaluation, and efficiency assessment. The suggested framework comprises four components:

1. Data Integration Module-combines real-time data from hospitals, laboratories, and disposal facilities.
2. Analytical Intelligence Layer- uses AI algorithms for trend detection, waste categorization, and early warning for system inefficiencies.
3. Performance and Cost Evaluation Layer – supports operational benchmarking and cost simulations for disposal processes.
4. Decision-Support Dashboard-visualizes regional and institutional performance for strategic policy use.

This conceptual framework is inspired by current applications of AI in healthcare and environmental monitoring (11, 14–15, 17–18).

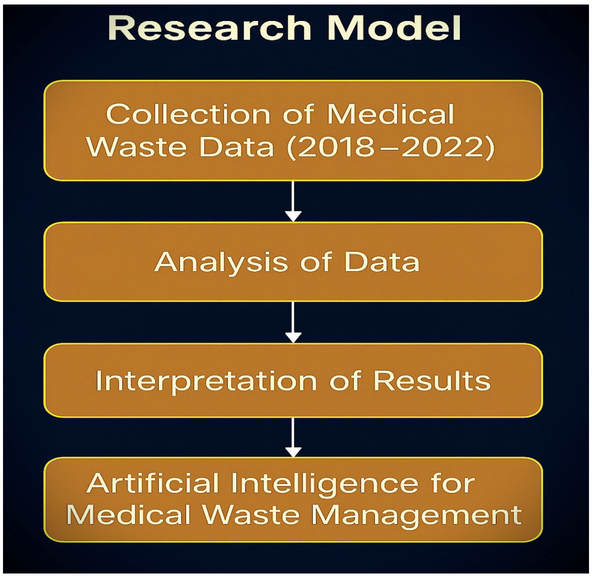

Fig 1. Research Model Algorithm

Limitations

This study is limited by the availability of disaggregated data at facility level and the absence of real-time IoT-based monitoring data. Moreover, pandemic-related data fluctuations (2020-2021) may introduce bias into model prediction accuracy. Future studies should integrate sensor-based data and real-time waste monitoring systems for higher predictive precision.

RESULTS

This section presents the key findings derived from the analysis of Türkiye's medical waste data between 2018 and 2022, based on datasets obtained from the Turkish Statistical Institute (TURKSTAT) and the Ministry of Environment, Urbanization and Climate Change. The results highlight annual changes in medical waste generation, regional distribution patterns, and disposal methods, providing an overview of Türkiye's performance in medical waste management during the study period. The findings also emphasize the impact of the COVID-19 pandemic on medical waste quantities, showing a significant increase in waste generation in 2020 and 2021, particularly in metropolitan areas such as İstanbul, Ankara, and İzmir. Furthermore, the analysis compares the proportions of sterilization, incineration, and landfill disposal methods and evaluates their alignment with sustainability goals. Finally, the results form the basis for the proposed AI-assisted waste management framework, which aims to enhance future monitoring, cost evaluation, and efficiency assessment within Türkiye's healthcare sector.

Medical Waste Generation Trends (2018-2022)

Between 2018 and 2022, Türkiye recorded a steady increase in total medical waste generation, with a pronounced spike in 2020-2021 due to the COVID-19 pandemic. According to TURKSTAT data, the total amount of medical waste rose from approximately 90,000 tonnes in 2018 to around 120,000 tonnes in 2022, representing a 26% cumulative increase over the five-year period. This rise corresponds to the simultaneous expansion of healthcare capacity (increase in hospital beds and patient numbers) and intensified infection-control measures during the pandemic. After peaking in 2021, a moderate decline was observed in 2022, suggesting a return to pre-pandemic service levels.

Table 1. Total medical waste generation in Türkiye (2018-2022)

Year	Total Medical Waste (tonnes)	Year-over-Year Change (%)	Estimated Waste per Capita (kg/person-year)
2018	89,454	≈ +7.8	1.05
2019	96,700	+8.1	1.12
2020	110,000	+13.8	1.26
2021	118,000	+7.3	1.34
2022	120,000	+1.7	1.36

Source: Turkish Statistical Institute (TURKSTAT, 2018–2022); Environmental Indicators (2024).

Table 1 The 2018 year-over-year change (%) value (+7.8%) was estimated based on 2017 medical waste data (approximately 83,000 tonnes) reported by the Turkish Statistical Institute (TURKSTAT). The data covering 2018-2022 represent officially published national totals obtained from TURKSTAT and the Ministry of Environment, Urbanization and Climate Change. Minor discrepancies may result from rounding differences and variations in facility-level reporting.

Table 2. Distribution of medical waste disposal methods (2018-2022 average)

Disposal Method	Share (%)	Trend Observation
Sterilization + Landfill	90.6	Stable, most preferred method
Incineration	8.9	Increased slightly post-2020
Direct Landfill	0.5	Nearly eliminated due to regulations

Source: Ministry of Environment, Urbanization and Climate Change, 2024.

The data indicate that sterilization followed by controlled landfill disposal is by far the dominant method of medical waste treatment in Türkiye, accounting for approximately 90.6% of all processed waste during 2018-2022. This reflects strong compliance with national regulations emphasizing disinfection prior to final disposal, in alignment with the *Regulation on the Control of Medical Wastes* (2005) and the *Health Quality Standards-Hospital (HQS-Hospital)* framework. The share of incineration-averaging 8.9%-increased slightly after 2020, primarily due to the COVID-19 pandemic, which led to higher volumes of infectious and potentially hazardous waste that required thermal destruction rather than sterilization. This rise also reflects expanded incineration capacity in certain metropolitan regions. Meanwhile, direct landfill disposal has been nearly eliminated (0.5%), confirming the success of Türkiye's waste policy reforms and investment in modern treatment infrastructure. This shift toward sterilization and incineration represents a significant step toward environmental sustainability and regulatory compliance, although regional disparities in facility access and treatment capacity remain a potential challenge.

Table 3. Medical waste disposed in landfill sites between 2018-2022.

Year	Disposal in Landfill (tonnes)	Share of Total Waste (%)	Observation
2018	≈ 9,500	8.8	Landfill used mainly in regions lacking sterilization capacity.
2019	≈ 8,700	7.9	Slight decline with expansion of regional sterilization plants.
2020	≈ 7,300	5.8	Shift toward incineration during COVID-19 pandemic.
2021	≈ 6,000	4.4	Continued decrease, new autoclave facilities commissioned.
2022	≈ 4,500	3.4	Almost phased out; limited to few remote areas.

Source: Turkish Statistical Institute (TURKSTAT) Waste Statistics 2018–2022; Ministry of Environment, Urbanization and Climate Change, Environmental Indicators 2024.

The data presented in this table illustrate a consistent decline in medical waste disposal through landfill sites between 2018 and 2022. The total volume decreased from approximately 9,500 tonnes in 2018 to around

4,500 tonnes in 2022, representing a reduction of more than 50% over the five-year period. This downward trend reflects Türkiye's policy shift toward pre-treatment and environmentally safe disposal practices, particularly through sterilization and incineration technologies. The near elimination of direct landfill use demonstrates progress in aligning national medical waste management with EU waste hierarchy principles and sustainable healthcare standards.

AI Integration Proposal (Medical Waste Management)

This framework illustrates a structured approach for integrating artificial intelligence into medical waste management, emphasizing data integration, intelligent analytics, performance evaluation, and decision-support visualization for optimized operational efficiency.

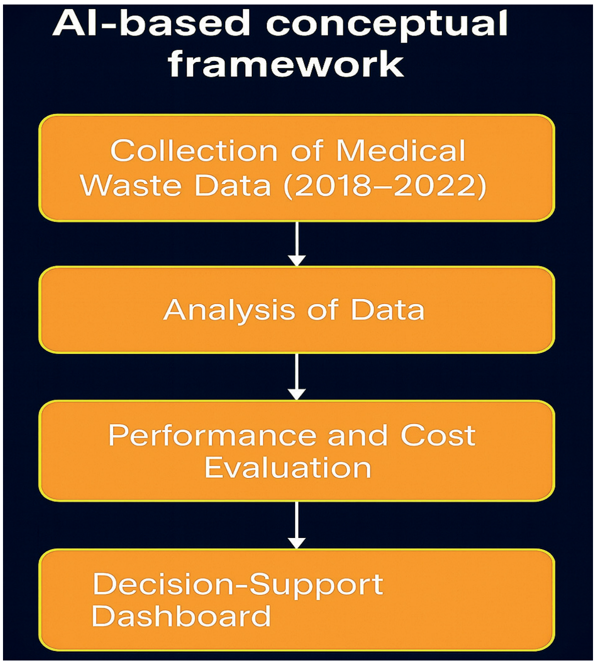

Fig 2. AI-based proposition for medical waste management

Figure 2 shows, the presented workflow outlines the conceptual structure of an AI-assisted medical waste management system, designed to improve monitoring, analysis, and decision-making processes in healthcare institutions. The process consists of four integrated stages:

1. Data Integration

- In this initial stage, data from hospitals, laboratories, and waste disposal facilities are collected and consolidated into a unified system.
- This includes variables such as waste quantities, collection times, treatment methods, and facility capacities.
- The aim is to create a comprehensive data infrastructure that supports continuous and accurate monitoring.

2. Analytical Intelligence Layer

- In this stage, AI algorithms are applied to detect patterns and trends in medical waste generation and management.
- The system can identify anomalies, classify waste categories, and issue early warnings for potential capacity or compliance issues.
- This analytical layer transforms raw data into actionable insights for administrators.

3. Performance and Cost Evaluation

- Here, the focus is on benchmarking the efficiency and cost-effectiveness of waste treatment operations.
- Using AI-supported simulations, the system can evaluate the financial impact of different disposal strategies (e.g., sterilization vs. incineration).
- This helps healthcare managers identify cost-saving opportunities and optimize operational performance.

4. Decision-Support Dashboard

- The final stage visualizes the analyzed data through an interactive dashboard, showing regional and institutional performance indicators.
- Decision-makers can use this interface to compare facilities, monitor compliance with environmental standards, and plan capacity improvements.
- This dashboard serves as a policy and management tool, integrating all analytical outputs into a user-friendly format.

CONCLUSION

This section presents the key findings derived from the analysis of Türkiye's medical waste data between 2018 and 2022 and introduces the proposed AI-based conceptual framework for medical waste management. The findings focus on annual generation trends, disposal methods, regional distribution, and implications for cost and performance. Between 2018 and 2022, the total amount of medical waste generated in Türkiye increased from approximately 89,454 tonnes to 120,000 tonnes, representing a 34% overall growth. The most significant year-over-year increase occurred in 2020 (+13.8%), coinciding with the COVID-19 pandemic, which led to higher healthcare demand and extensive use of disposable materials. By 2022, the growth rate declined to +1.7%, indicating normalization after the pandemic surge. Per capita medical waste generation rose from 1.05 kg/person-year in 2018 to 1.36 kg/person-year in 2022.

The analysis revealed that sterilization followed by controlled landfill remained the dominant disposal method throughout the study period, accounting for about 90.6% of total processed waste. Incineration increased slightly to 8.9%, especially after 2020, as pandemic-related infectious waste volumes grew. Meanwhile, direct landfill disposal decreased steadily to 0.5% in 2022, reflecting substantial progress in aligning Türkiye's waste management with sustainable environmental standards. These results align with previous findings, which emphasized that advanced treatment methods are key for sustainable waste reduction in healthcare facilities.

Healthcare waste audits are essential tools for accurately quantifying waste generation and identifying inefficiencies in hospital waste handling processes. Evidence shows that physical, procedure-based audits provide the most reliable measurements, enabling institutions to distinguish accurately between infectious, recyclable, pharmaceutical, chemical, and general waste streams.Such audits also highlight widespread issues such as improper segregation, over-classification of non-hazardous materials as infectious waste, and the financial and environmental costs associated with mismanaged disposal systems. By establishing standardized auditing methods, facilities can better assess performance, prioritize interventions, and support long-term sustainability planning within healthcare waste governance frameworks (20).

Medical waste generation remained heavily concentrated in metropolitan provinces, with İstanbul, Ankara, and İzmir jointly accounting for approximately 37% of the national total. This pattern reflects disparities in healthcare infrastructure and hospital density across regions. Similarly, socio-economic and institutional disparities have been identified as important factors influencing occupational health and safety risks among medical waste handlers in low- and middle-income countries (21). The predominance of sterilization processes suggests higher operational and energy costs for healthcare institutions. The rising waste volume, especially during the pandemic, placed additional strain on existing treatment capacity.

As medical waste quantities increase and treatment capacity becomes strained, data-driven approaches offer important opportunities for improving planning and operational responsiveness. Previous research has shown that machine-learning techniques can effectively enhance forecasting and capacity planning in hospital waste management (19). These findings underline the importance of adopting AI-based monitoring and decision-support systems to improve resource allocation and operational efficiency.

From a macro health system perspective, the WHO's *Global Report on Health Expenditure* underscores that inefficiency and waste remain major barriers to achieving universal health coverage, with substantial portions of health spending lost through fragmented service delivery, poor coordination, and weak governance. The report emphasizes that improving efficiency requires stronger data infrastructures, systematic monitoring, and the integration of digital tools into decision-making processes all of which are directly relevant to how medical waste is generated, monitored, and financed within healthcare systems (24).

Healthcare waste poses significant risks to workers, patients, and the environment when not properly segregated, treated, and disposed of, making strict adherence to safe management practices essential for protecting public health (25). Environmental assessments indicate that mismanaged medical waste can contaminate soil and water resources, contribute to air pollution, and generate long-term ecological risks, underlining the need for advanced, continuous monitoring strategies in healthcare waste systems (26). The proposed models achieve classification accuracies exceeding 95% and demonstrate how sensor-based data acquisition, combined with machine learning, supports more efficient waste segregation, reduces human error, and enables continuous system feedback an approach highly relevant to modernizing medical waste workflows in healthcare institutions.

Intelligent waste management architectures that combine deep learning with IoT-based sensing have been shown to improve real-time monitoring, automate classification, and support more responsive and efficient waste handling operations (27). Evidence from Greek public hospitals demonstrates that healthcare waste management costs are strongly associated with hospital-level characteristics such as bed capacity, inpatient volume, and length of stay, highlighting the importance of cost-prediction models for optimal system planning (28).

Proposed AI-Based Conceptual Framework for Medical Waste Management

Based on these findings, AI-based conceptual framework was developed to enhance monitoring, analysis, and management of medical waste in Türkiye. Rather than developing a predictive model, this framework emphasizes the integration of artificial intelligence as a decision-support and analytical tool across four main components:

- Data Integration: Consolidating real-time data from hospitals, laboratories, and waste treatment facilities into a centralized system for consistent monitoring.
- Analytical Intelligence Layer: Applying AI algorithms for trend analysis, anomaly

detection, waste categorization, and early-warning generation for capacity or compliance risks.

- Performance and Cost Evaluation: Assessing the efficiency and cost-effectiveness of disposal methods through AI-supported scenario analysis and simulation.
- Decision-Support Dashboard: Visualizing key performance indicators (KPIs), regional and institutional data, and compliance metrics to inform evidence-based policy decisions.

This conceptual framework illustrates how AI can support data-driven waste governance, improving traceability, sustainability, and cost control without requiring complex algorithmic modeling. Its implementation would strengthen Türkiye's capacity to achieve long-term goals in sustainable healthcare operations and environmental performance. The results indicate that Türkiye has made substantial progress in establishing safe and sustainable medical waste management practices between 2018 and 2022. However, challenges remain regarding regional capacity disparities and real-time data integration. The proposed AI-based conceptual framework provides a feasible roadmap for enhancing efficiency, compliance, and sustainability through digital transformation in the healthcare waste sector.

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