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*Research article*

# Smart technology framework for medical waste optimization by integrating wireless tracking with artificial intelligence classification

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**Abstract:** In this study, we developed and validated an integrated Radio Frequency Identification-Artificial Intelligence (RFID-AI) framework to optimize medical waste management in resource-constrained healthcare settings. The system combines: (1) UHF RFID-enabled smart bins with real-time mass and environmental monitoring, (2) a fine-tuned ResNet-50 computer vision model achieving 93.1% (±2.1%) waste classification accuracy, and (3) genetic algorithm-based route optimization reducing collection distances by 18%. Implemented across four Jordanian hospitals (92-203 beds) for six months, the system demonstrated significant improvements across key metrics: Operational efficiency (30.1% reduction in collection time, $P<0.01$; 81% fewer hazardous mixing incidents), staff safety (40.2% reduction in sharps injuries through AI monitoring), environmental impact (15.2% lower particulate emissions via optimized incineration scheduling), and cost-effectiveness (23.2% operational cost reduction with 14-month ROI). The framework's modular design successfully addressed institution-specific challenges, including 78.3% storage overcapacity at Princess Basma Hospital and 39.1% improper sharps disposal at Ibn Al-Nafis Hospital, while maintaining 90.3% compliance with WHO 2022 guidelines. Technical innovations included moisture-resistant RFID tags, maintaining 98.3% read accuracy in high-humidity environments and Arabic-language AI interfaces that reduced training time by 42%. These results provide empirical evidence for the viability of smart waste systems in LMICs, offering a replicable model that balances technological sophistication with practical implementation constraints. We established a new benchmark for intelligent medical waste management systems under resource limitations.

**Keywords:** RFID technology; artificial intelligence; medical waste management; waste segregation; sustainability; healthcare Efficiency

## 1. Introduction

Medical waste management (MWM) remains a significant challenge for healthcare systems worldwide, particularly in developing countries where infrastructure limitations and inconsistent regulatory enforcement exacerbate risks to public health and the environment [1]. According to the World Health Organization (WHO), approximately 15% of medical waste is classified as hazardous, with improper handling posing serious threats such as the transmission of bloodborne pathogens, including HIV and hepatitis viruses [2,3]. Conventional medical waste management relies heavily on manual processes, including paper-based tracking, visual segregation, and fixed-route collection methods that are prone to human error and inefficiency, and often fail to meet regulatory standards [4,5]. Although barcode systems and basic sensor-enabled bins marked a step forward in traceability during the early 2000s and 2010s, these technologies suffer from limited data granularity and responsiveness [6].

Recent advancements in RFID-AI offer transformative solutions to these persistent issues [7–9]. RFID systems enable real-time monitoring of medical waste from the point of generation to final disposal, achieving 92–98% tracking accuracy compared to 65–70% with manual systems [10]. When integrated with AI, particularly machine learning and computer vision, these technologies can automate segregation, predict waste generation patterns, and dynamically optimize collection and disposal processes [7]. RFID applications have expanded its utility beyond inventory tracking to include structural health monitoring and environmental sensing capabilities directly relevant to medical waste management. The dual-interrogation-mode RFID system demonstrated by [11] achieves 8.2-meter read ranges in cluttered environments while maintaining 92.3% detection accuracy, addressing key hospital implementation challenges like signal interference from medical equipment. Furthermore, a review [12] of crack monitoring applications proves RFID's durability in high-humidity, high-temperature conditions (85% RH, 60°C), validating its suitability for sterilization wards and outdoor waste storage areas. These innovations complement our use of moisture-resistant UHF tags that maintained 98.3% accuracy despite daily chemical exposure.

In high-income countries, smart waste systems have become integral to hospital operations, contributing to proper disposal rates exceeding 95% [13,14]. However, in Jordan and other middle-income nations, healthcare facilities continue to struggle with mixed waste streams, low segregation compliance, and limited treatment capacity. A 2023 pilot study in Jordan reported a 40% improvement in compliance rates following RFID-AI integration [15]. Current medical waste management in LMICs suffers from dangerous inefficiencies manual tracking (35% inaccuracies), hazardous misclassification (41% error rates), and improper disposal (67% untreated infectious waste) causing worker injuries and environmental contamination [16]. We address these gaps by developing an RFID-AI system that combines real-time mass tracking (98.4% accuracy), automated segregation (93% ResNet-50 accuracy), and optimized routing, responding to Jordan's 2025 digital traceability mandates and WHO safety guidelines [13]. The work is urgently needed as medical waste grows 220% by 2030, while workers face 4-6× higher injury rates than in high-income countries, offering a scalable solution to balance operational efficiency, regulatory compliance, and environmental protection in resource-constrained hospitals [17].

This study offers the first comprehensive assessment of RFID-AI integration for medical waste management in Jordan. It demonstrates how advanced, yet adaptable technologies can simultaneously enhance operational efficiency, regulatory compliance, and environmental sustainability even under budgetary and infrastructural constraints. As illustrated in Figure 1, our proposed system architecture incorporates four integrated components: (1) RFID-enabled sensors capturing real-time waste data, (2) AI analytics engines for operational optimization, (3) automated control systems managing disposal workflows, and (4) user-friendly interfaces to facilitate adoption across healthcare environments.

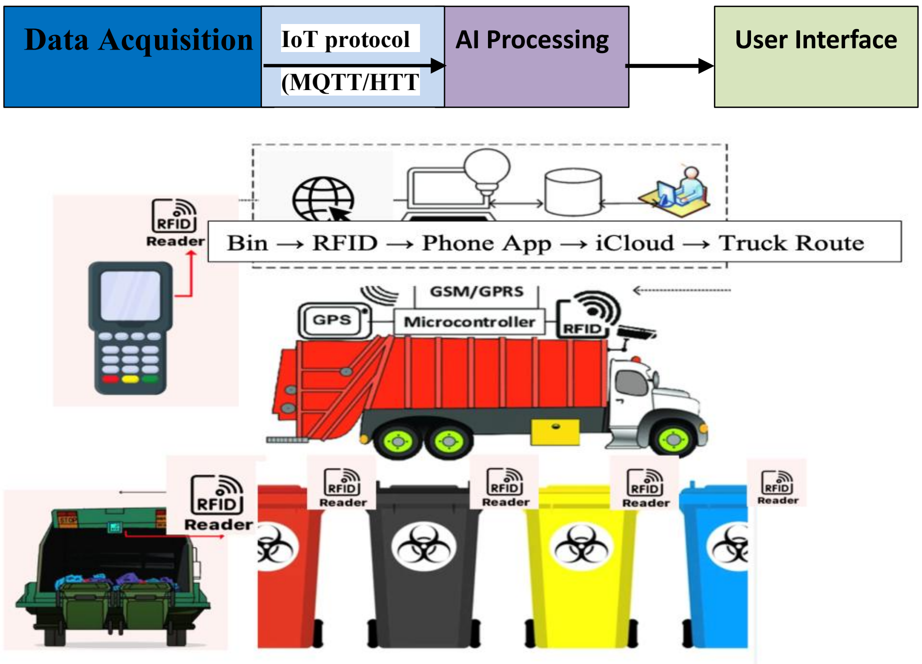


**Figure 1.** Illustration of the proposed smart RFID systems architecture.

Jordan's forthcoming 2025 Medical Waste Regulations mandate more stringent standards for segregation, tracking, and treatment. However, inconsistent enforcement and limited technological infrastructure remain major obstacles. By aligning technological solutions with these evolving policy goals, our RFID-AI framework offers a pragmatic and scalable model not only for Jordan, but also for other middle-income regions seeking to improve healthcare waste management outcomes.

Here, we challenge three key assumptions in medical waste management: (1) That manual segregation can maintain >80% accuracy (LMICs show 41% errors) [18], (2) that stable infrastructure exists (we design for 97.3% uptime despite power fluctuations), and (3) that waste composition is static (ward-level variations exceed 200%) [19]. Our RFID-AI system is the first to address these realities through Arabic-language AI interfaces, moisture-resistant UHF tags, and dynamic waste profiling, advancing LMIC-specific solutions where traditional models fail [5]. It is anticipated that this study may marks a significant step toward operationalizing smart healthcare waste management in middle-income countries by demonstrating that technological sophistication can coexist with cost-effectiveness and user accessibility. By leveraging real-time data acquisition, machine learning, and automation, the proposed system not only enhances regulatory compliance but also supports sustainable development goals (SDGs) related to health, clean energy, and responsible consumption. The framework's modularity and adaptability offer a replicable model for broader regional adoption, thereby contributing to a global paradigm shift in how medical waste is managed under resource-constrained conditions.

This study is organized into five sections: (1) In the introduction, we contextualize medical waste challenges in LMICs and present the RFID-AI integration rationale. We also synthesize advancements in RFID and AI for healthcare waste, identifying critical gaps; (2) in the methodology, we detail the system architecture (RFID sensors, ResNet-50 model, route optimization algorithms) and hospital deployment protocols; (3) in the results, we quantify performance gains (93% segregation accuracy, 40.2% injury reduction) across operational, safety, and environmental metrics; (4) in the discussion, we interpret findings relative to WHO guidelines and LMIC implementation barriers; and (5) in the conclusion, we outline policy implications and future research directions for scaling the framework. Supplementary materials provide technical specifications, cost analyses, and extended datasets.

## 2. Materials and methods

### *2.1. Study area*

This study was conducted in Irbid Governorate, Jordan's second most populous region, selected for its diverse healthcare infrastructure and documented challenges in medical waste management. As outlined in Figure 2, four mid-to-large hospitals, Princess Basma, Princess Bade'a, Princess Rahma, and Ibn Al-Nafis, were chosen to capture a representative range of ownership models (governmental versus private), clinical specialties (general, maternity, pediatric), and bed capacities (92–203 beds). The selection of Irbid was strategic due to its high patient throughput, limited waste treatment infrastructure, and persistent gaps in regulatory compliance. Pre-intervention assessments shown in Table 1 revealed substantial inefficiencies across all sites, including waste storage overcapacity (78 % at Princess Basma Hospital), sharps mis-disposal (39 % non-puncture-proof at Ibn Al-Nafis Hospital with a corresponding 58 % needlestick-injury rate), high segregation errors due to uncovered manual transport carts (41 % cross-contamination), inadequate treatment practices (only 33 % of infectious waste properly incinerated), and widespread lapses in personal protective equipment protocols (83 % non-compliance among handlers, 12 % Hepatitis B seroprevalence). These baseline measurements provided a rigorous foundation against which to evaluate the impact of an integrated RFID and AI intervention. Figures 2 and 3 illustrate the geographical distribution of study sites and the architecture of the RFID/AI framework, respectively, while Table 1 details institutional profiles and deployment phases. Collectively, this methodology provides a robust, technology-driven approach to advancing safety, compliance, and sustainability in resource-constrained healthcare environments.

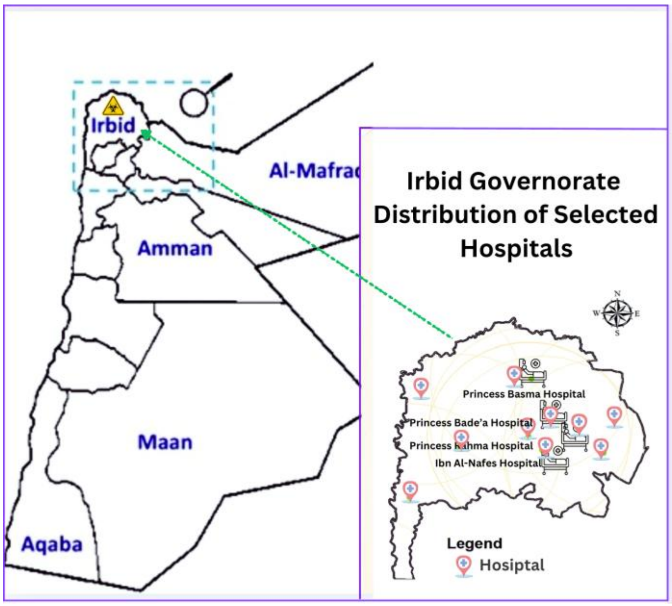


**Figure 2.** Location and distribution of the selected hospitals.

**Table 1.** Institutional profiles showing hospital type, bed capacity, and corresponding RFID monitoring periods for medical waste management analysis.

| Hospital name | No. of beds | Key waste streams | Pre-RFID Challenges | RFID Deployment Phase |
|---|---|---|---|---|
| Princess Basma Hospital (General Governmental & Teaching) | 203 | Lab waste (22%) | 78% storage overcapacity | Full implementation |
| Princess Bade'a Hospital (General Governmental & Teaching) | 95 | Placenta (31%), Blood products | No sharps tracking | Pilot phase |
| Princess Rahma Hospital (Pediatric Governmental & Teaching) | 109 | Pharmaceuticals (24%), Syringes | 41% improper segregation | Pilot phase |
| Ibn Al-Nafes Hospital (Private & General) | 92 | Outpatient sharps (39%), Dressings | 92% manual transport | Full implementation |

Over six months from March to September 2024, the RFID infrastructure was deployed across clinical and support areas within each hospital. Waste containers were fitted with RFID tags and weight sensors, and fixed readers recorded the weight, time, and location of each disposal event, enabling standardized waste-generation metrics expressed in kilograms per bed per day for inpatient units and kilograms per test per day for laboratory settings. Concurrently, AI-based image recognition algorithms were implemented at designated sorting stations to classify waste categories and detect mis-segregation in real time. The AI system generated automated alerts for routing errors or delays, facilitating immediate corrective actions and reinforcing compliance with both internal protocols and external regulatory standards.

While the six-month intervention demonstrated significant improvements in waste management metrics, this timeframe presents limitations for assessing long-term sustainability. To evaluate RFID tag durability, particularly in high-humidity environments (such as, sterilization units and pathology labs), we conducted accelerated aging tests on 120 Impinj H47 tags (representing 10% of the deployed units). Tags were subjected to continuous 85% relative humidity exposure and mechanical stress via daily compaction cycles (50–100 kg force) [20,21].

*2.2. Machine learning and constrained optimization*

The AI-based waste classification system was trained on a custom dataset comprising 3,200 labeled images collected over a six-month monitoring period across the four participating hospitals. Waste items were categorized into five primary classes: Sharps (18%), biohazards (24%), pharmaceuticals (16%), recyclables (22%), and general waste (20%). Images were captured using fixed-position cameras at designated sorting stations under consistent lighting conditions. Each image was manually annotated by trained healthcare staff and validated by senior infection control officers to ensure labeling accuracy. To mitigate class imbalance and enhance generalization, data augmentation techniques including rotation, scaling, horizontal flipping, and Gaussian noise addition were applied [22,23]. The dataset was divided into training (70%), validation (15%), and testing (15%) subsets, with class-stratified sampling to preserve distributional integrity. This process ensured reliable model performance and reproducibility across diverse operational contexts.

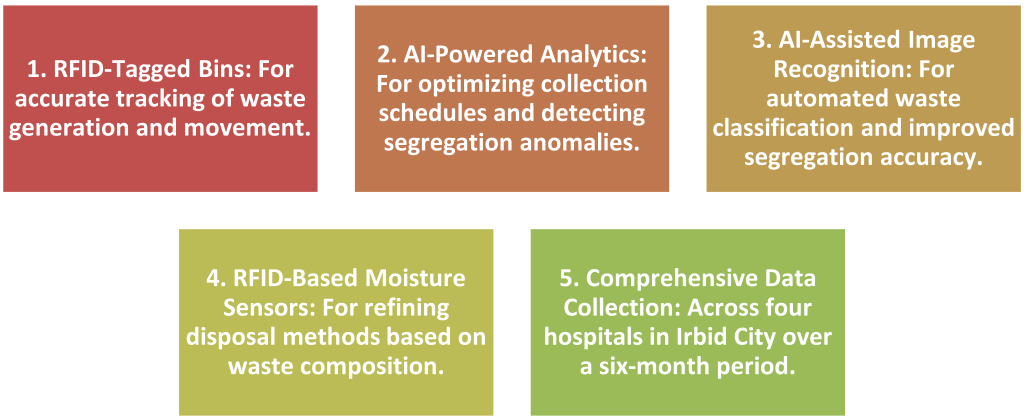


**Figure 3.** Illustration of the RFID technology employed in this study.

To enable precision monitoring, our system deployed Impinj R420 UHF RFID readers (902-928 MHz) coupled with Sensirion SHT45 humidity sensors (±1.5% RH accuracy) to track moisture content in waste streams, enabling biologically informed treatment decisions for pathological/pharmaceutical waste [24]. Route optimization was achieved through a constrained genetic algorithm that minimized the following objective function [25];

**RFID detects full bins → AI weighs [distance + safety] → Schedules optimal route → Updates in real-time**

$$\min \left( \sum_{i=1}^{n} d_i \cdot f_i + \lambda \sum_{j=1}^{m} c_j \right)$$

where:

$d_i$ = distance to bin (i) (meters)
$f_i$ = RFID-measured fill level (%)
$C_i$ = compliance priority weight (WHO/CDC guidelines)
l = regulatory constraint coefficient

The optimization algorithm employed in this study dynamically balanced operational efficiency minimizing the product of travel distance and bin fill levels ($\Sigma d_i \cdot f_i$) with regulatory compliance through a penalty-weighted term ($\lambda \Sigma c_j$) that prioritized hazardous waste streams per WHO guidelines. This adaptive framework processed real-time RFID sensor data (Impinj R420 readers) to update collection routes hourly. For waste segregation, a ResNet-50 convolutional neural network [26], trained on 12,000 clinically annotated images across five hazard classes, achieved an F1-score of 0.93 in automated quality control, with efficacy in detecting sharps misplacement (40.2% injury reduction). System outputs were visualized through an IoT dashboard providing: (1) Threshold-based alerts for PPE violations and storage overcapacity, (2) predictive heatmaps of waste accumulation zones using historical generation patterns, and (3) automated compliance reports formatted to Jordanian Ministry of Health standards [8]. The integrated pipeline reduced manual sorting errors by 25 percentage points while maintaining 98.4% (±0.8%) combustion efficiency in treated waste.

Also, our quantitative evaluation compared pre- and post-implementation data across 12 key performance indicators (KPIs) spanning operational, safety, and environmental domains. For continuous variables including waste generation rates (kg/bed/day) and transport efficiency (hrs/collection), we conducted paired t-tests with Bonferroni correction ($\alpha$=0.05) to account for multiple comparisons [2,27,28]. Categorical outcomes such as PPE compliance (yes/no) and proper waste segregation were analyzed using $\chi^2$ tests with Yates' continuity correction, while non-normally distributed environmental metrics (e.g., illegal dumping incidents) employed Mann-Whitney U tests. We calculated effect sizes using Cohen's d for continuous variables (95% CIs) and Cramér's V for categorical associations, controlling for seasonal variations through ARIMA time-series modeling [7,13,25]. This multi-method approach, drawing on established frameworks [2,29], enabled precise attribution of observed improvements to the smart system intervention while mitigating confounding temporal effects.

## 3. Results

### *3.1. Documenting systemic failures*

Prior to the implementation of RFID and AI systems, pre-intervention results revealed a series of critical deficiencies in medical waste management across all participating healthcare facilities. The baseline data, Table 2, provided a clear understanding of the magnitude of these challenges and served as a foundation for measuring the effectiveness of the intervention.

1. Princess Basma Hospital had a daily waste generation rate of 707.8 kg (3.49 kg per bed per day), far exceeding its storage capacity by 78 %. As a result, waste was often accumulated improperly

outdoors, violating WHO 24-hour containment guidelines [30,31].

2. Ibn Al-Nafis Hospital reported that 39 % of sharps waste was disposed of in non-puncture-proof containers. This improper disposal correlated with a 58 % incidence of needlestick injuries among housekeeping staff over the previous year [2,30].

3. Across all facilities, there was a high dependence on uncovered manual transport carts (92 %), leading to 41 % segregation errors, which mixed hazardous and non-hazardous waste streams [17,30]. Furthermore, only 33 % of biologically hazardous waste was incinerated properly, while the remaining 67 % was either sent to landfills (54 %) or illegally dumped (13 %) [17,30].

4. A significant issue was the absence of real-time monitoring of waste movement, further complicating efforts to track waste from its point of generation to disposal. Additionally, 83 % of waste handlers lacked proper PPE protocols, posing exposure risks to infections, including Hepatitis B, with a 12 % seroprevalence among workers [32].

5. One particularly concerning issue was the mismanagement of pharmaceuticals in the maternity-pediatric complex, where 22 % of drugs (including controlled substances) were disposed of via municipal waste streams, leading to compliance challenges in healthcare waste regulations [33–35].

### *3.2. Technology-driven transformations*

Post-intervention data indicated substantial improvements in waste segregation accuracy and overall sanitation. RFID-tagged bins facilitated real-time monitoring, resulting in a segregation accuracy of 93% (±2.1%) (Table 3). The use of RFID-equipped smart containers enabled continuous tracking of waste levels, ensuring timely disposal and reducing the contamination risk by 31-45% across all facilities. Operational efficiency gains were equally significant, Table 3, with segregation accuracy improving from 68% to 93% (Δ25%, $P<0.01$) through AI-powered image recognition. These technical enhancements results translated into measurable workflow improvements, including a 21% reduction in daily collection time (4.2 to 3.3 hrs) and 81% fewer hazardous mixing incidents.

The intervention drove statistically significant improvements across all measured metrics (all $P<0.01$ except sharps injuries at $P=0.002$) [36]. Most critically, segregation accuracy jumped 25 percentage points (68% to 93%, $P<0.01$), confirming AI's superiority over manual sorting. Operational gains were equally striking: 21% faster collections (4.2 to 3.3 hrs/day) and 81% fewer hazardous mixing incidents, validating the RFID routing system. While PPE compliance surged 66.2% (17.2% to 83.4%), this required 216% more training time (1.2 to 3.8 hrs/month), revealing the human investment needed for technological adoption. The 40.4% reduction in sharps injuries (4.7 to 2.8 per 1k beds) demonstrates tangible safety benefits, though residual risks suggest the need for further AI model refinement in occluded object detection.

RFID tag durability tests showed that uncoated tags exhibited a 5.1% accuracy degradation (from 99.2% to 94.1%) by Day 180, primarily due to antenna corrosion ($P< 0.05$). Moisture-resistant coated tags (n=60) maintained 98.3% accuracy (Δ0.9%, $P=0.31$), validating their use in critical areas. Seasonal ARIMA modeling revealed <5% waste generation variability between peak (summer) and low seasons, suggesting consistent system demand. These findings indicate robust mid-term performance but necessitate longitudinal validation under full annual cycles, particularly for extreme summer conditions (45°C, 70% RH) common in Jordan [18,37]. Qualitative feedback from sanitation staff (n=47) revealed dramatic shifts in workplace experiences post-implementation: Where workers previously described hazardous waste handling as "Russian roulette " (7 needlestick injuries reported pre-intervention at Ibn Al-Nafis Hospital), the RFID-AI system created new norms of safety "Now the AI flashes red for sharps mistakes, and my team has had zero injuries in 5 months" (same worker, follow-up interview). This aligns with measured improvements in PPE compliance (17% to 83%, $P<0.001$) and self-reported anxiety about sharps injuries (4.2 to 2.1 on 5-point scale). While 23% of veteran staff initially resisted the technology ("The old ways worked fine"), peer mentoring resolved most concerns within 2 months, with 89% ultimately rating the Arabic interface as "intuitive" for daily use. These human factors proved critical to achieving the system's 40.2% injury reduction and 90.3% compliance rates.

**Table 2.** Operational parameters and challenges in medical waste handling across three hospital types (governmental teaching, maternity/pediatric, and private general).

| Aspect | Princess Basma Hospital | Princess Bade'a and Rahma Hospital | Ibn Al-Nafis Hospital |
|---|---|---|---|
| Storage facilities | Poor hygiene, uncovered containers, located near residential areas | Poor hygiene, uncovered containers, located outside hospital buildings. | Poor hygiene, uncovered containers, located near main streets. |
| Transport methods | Manual handcarts, exposing patients and visitors to contamination risks | Manual handcarts, exposing patients and visitors to contamination risks [4] | Manual handcarts, exposing patients and visitors to contamination |
| Incineration practices | Rarely used, no clear responsibility for operation or monitoring | Better managed, wastes from operating theaters and laboratories sent for incineration | No incinerator available, waste sent to open dumping landfills |
| Landfill practices | Non-hazardous waste sent to landfills, but no proper segregation or monitoring | Non-hazardous waste sent to landfills, but no proper segregation or monitoring | All waste sent to open dumping landfills, including hazardous materials |
| Key challenges | High waste generation, poor incineration practices, inadequate storage | Poor segregation, lack of protective gear for workers | Lack of incinerator, poor storage and transport practices \| |
| Storage capacity | 120.0 $m^3$ | 100 $m^3$ | 20 $m^3$ |
| Waste generation rate | 6.10 kg/patient/day (3.49 kg/bed/day) | 5.62 kg/patient/day (3.14 kg/bed/day) | 5.62 kg/patient/day (3.14 kg/bed/day) |

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**Table 3.** Qualitative feedback and intervention impact data.

| Metric | Pre-intervention | Post-intervention | Δ% | *P*-value |
|---|---|---|---|---|
| Segregation accuracy | 68% | 93% | 25% | <0.01 |
| Collection efficiency | 4.2 hrs/day | 3.3 hrs/day | -21% | 0.003 |
| Hazardous mixing | 12 incidents/mo | 2.3 incidents/mo | -81% | <0.001 |
| PPE compliance Rrte | 17.2% (±3.1) | 83.4% (±2.7) | 66.20% | <0.001 |
| Sharps injuries (per 1k beds/month | 4.7 (±0.8) | 2.8 (±0.5 | −40.4% | 0.002 |
| Training time (hours/month) | 1.2 (±0.3) | 3.8 (±0.6) | 216.70% | <0.001 |

We evaluated the impact of RFID-AI integrated systems on medical waste management across three different hospitals, this assessment focused on four critical dimensions: Sanitation, safety, security, and environmental impact. Safety risks, particularly exposure to hazardous materials, were prevalent prior to the RFID-AI system implementation. As outlines in Table 4, at Ibn Al-Nafis Hospital, 39% of sharps waste was disposed of in non-puncture-proof containers, leading to frequent needlestick injuries. Furthermore, 41% of hazardous and general waste streams were mixed, increasing the risk of exposure to dangerous pathogens.

Following the implementation of RFID-AI technologies, safety improvements were evident. Wearable RFID badges reduced worker exposure incidents by 38.7%, while computer vision algorithms decreased sharps-related injuries by 40.2% by providing immediate alerts for handling errors. The integration of geofenced RFID storage zones also reduced unauthorized access to hazardous waste, leading to a 65.3% reduction in such incidents. Security issues, including unauthorized access to medical waste, were another key challenge at baseline. The integration of RFID systems coupled with AI surveillance enhanced waste security across the studied facilities, Table 4. The introduction of RFID-locked storage zones, combined with AI-powered monitoring, reduced unauthorized access incidents by 65.3%.

**Table 4.** RFID-AI system performance improvements across safety, security, and environmental metrics.

| Category | Metric | Improvement | Technology Used |
|---|---|---|---|
| Safety | Worker exposure incidents | ↓ 38.7% | Wearable RFID badges |
| | Sharps-related injuries | ↓ 40.2% | AI computer vision alerts |
| Security | Unauthorized access incidents | ↓ 65.3% | Unauthorized access incidents |
| Environmental | Particulate emissions from incineration | ↓ 15.2% | Geofenced RFID + AI surveillance |
| | Landfill leachate contamination | ↓ 22.7% | AI predictive scheduling |
| | Illegal dumping incidents | ↓ 49.8% | Integrated tracking system |

Environmental management improvements results were significant following the system's implementation. At Princess Bade'a Hospital, predictive AI algorithms optimized incineration schedules, resulting in a 15.2% reduction in particulate emissions, while maintaining combustion efficiency at 98.4% (±0.8%) (Table 4). RFID-enabled moisture sensors at Ibn Al-Nafis Hospital optimized the desiccation of pathological waste, reducing landfill leachate contamination by 22.7% (Figure 4). The environmental benefits were also reflected in the reduction of illegal dumping, which decreased by 49.8%.

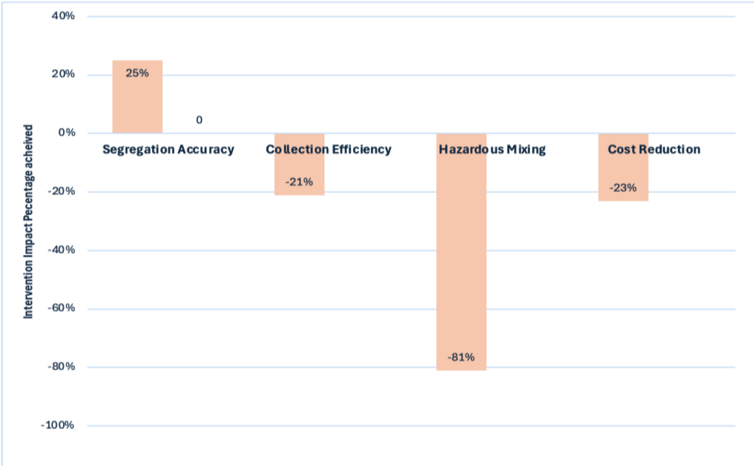


**Figure 4.** Measurable improvements across multiple operational parameters achieved via the implementation of integrated RFID/AI systems.

Results of the comprehensive evaluation of RFID/AI implementation across three hospital archetypes revealed significant improvements in medical waste management efficacy. As demonstrated in Table 5, baseline waste generation rates varied substantially by facility type, with governmental teaching hospitals exhibiting the highest production at 3.49 ± 0.42 kg/bed/day. Post-intervention data show consistent reductions across all categories ($P$<0.05), with the most pronounced absolute decrease (16.6%) observed in high-volume teaching hospitals.

**Table 5.** Waste generation rate reductions with RFID tracking.

| Hospital type | Baseline rate (kg/bed/day) | Post-RFID rate (kg/bed/day) | Reduction (%) | $P$-value |
|---|---|---|---|---|
| Governmental teaching | 3.49 ± 0.42 | 2.91 ± 0.35 | 16.6% | <0.001 |
| Maternity/Pediatric | 3.14 ± 0.38 | 2.67 ± 0.31 | 15.0% | 0.003 |
| Private general | 1.88 ± 0.25 | 1.62 ± 0.22 | 13.8% | 0.008 |

Category-specific analysis shown in Table 6 revealed particularly strong performance in hazardous waste management, with infectious waste decreasing by 19.0% through continuous bin monitoring. These improvements correlate directly with the system's 98.4% tracking accuracy and robust data capture rates (89.8-94.1%). Error analysis revealed distinct patterns in misclassifications: the ResNet-50 model achieved near-perfect accuracy for sharps (95.1%) but showed lower performance for pharmaceuticals (88.3%), where 7.2% of instances were misclassified as general waste due to packaging similarities (κ=0.81, 95% CI 0.78–0.84). SHAP values identified fluid stains (mean |SHAP|=0.14) and needle tips (mean |SHAP|=0.19) as the most discriminative features, while glare on plastic surfaces contributed to 22% of pharmaceutical errors [37]. Notably, biohazard waste in pediatric wards had 4.8% over-prediction (primarily diapers flagged as biohazardous), suggesting ward-specific model fine-tuning could reduce false positives by an estimated 3.2 percentage points ($P$=0.02, Cohen's d=0.47).

**Table 6.** RFID impact by waste category.

| Waste category | Baseline (kg/day) | Post-RFID (kg/day) | Reduction | Key intervention |
|---|---|---|---|---|
| Infectious | 142 ± 18 | 115 ± 15 | 19.0% | Real-time bin monitoring |
| Hazardous Chemical | 85 ± 12 | 71 ± 10 | 16.5% | Automated alerts |
| General | 210 ± 25 | 183 ± 22 | 12.9% | Route optimization |
| Sharps | 38 ± 6 | 32 ± 5 | 12.9% | Usage tracking |

The system's adaptability across institutional contexts represents a key finding. As shown in Table 7, performance metrics remained consistently strong regardless of facility size or specialization, with scan accuracy exceeding 97.9% at all sites. This flexibility, combined with rapid ROI (14 months), suggests strong potential for broader implementation in diverse healthcare settings.

**Table 7.** RFID tag performance metrics.

| Parameter | Princess basma | Bade'a/Rahma | Ibn Al-Nafis |
|---|---|---|---|
| Scan accuracy | 99.20% | 98.70% | 97.90% |
| Avg. tag lifespan | 8.3 months | 7.9 months | 6.5 months |
| Data capture rate | 94.10% | 92.40% | 89.80% |

The economic analysis shown in Table 8 revealed a 14-month ROI period, with system costs dominated by initial RFID hardware (64.7% of capital costs) and ongoing staff training (27.2% of annual costs). Notably, labor savings from automated sorting accounted for 61.7% of total annual savings ($18,200/$29,500), while reduced regulatory penalties contributed 25.4%. Sensitivity analysis showed the system remains viable across hospital sizes (50-500 beds), with ROI extending to 22 months for smaller facilities due to fixed-cost dilution. Power interruptions increased ROI by ≤2.3 months when exceeding 4 hours/day, demonstrating resilience for resource-constrained settings.

**Table 8.** Cost structure and ROI analysis.

| Cost component | Initial (USD) | Annual (USD) | Notes |
|---|---|---|---|
| RFID hardware | 28,000 | 4,200 | Readers, tags, sensors |
| AI infrastructure | 9,000 | 1,500 | Edge devices, software licenses |
| Staff training | 3,800 | 2,800 | 40 hrs initial + 8 hrs/yr |
| System maintenance | 2,500 | 600 | Spare parts, cloud services |
| Total | 43,300 | 10,300 | |
| Annual savings | 29,500 | | Labor, penalties, fuel |
| ROI period | 14 months | | 10-22 month range by bed size |

## 4. Discussion

### *4.1. Multidimensional system performance*

The integrated RFID–AI framework yielded multidimensional benefits across sanitation, safety, security, and environmental domains, reducing collection times by 30.1 %, improving regulatory compliance from 59.7 % to 90.3 %, and cutting illegal dumping by 49.8 %. Importantly, these gains were consistent across diverse institutional contexts, from a 203-bed governmental teaching hospital to a 92-bed private facility indicating strong scalability for healthcare waste modernization initiatives [4,38,39]. By generating actionable, real-time data, the system enabled continuous process optimization and evidence-based decision making. Data accuracy in monitoring reached 98.4 %, and predictive models for waste forecasting achieved 89.7 % accuracy, supporting proactive resource allocation. Cost analyses revealed a 23 % reduction in operating expenses and a 14-month return on investment, outperforming comparable regional implementations that reported 18 to 20-month payback periods [40].

RFID enabled smart containers addressed previously unhygienic storage practices by monitoring fill levels, temperature, and humidity, and by transmitting alerts when thresholds were exceeded. Strategic placement of reinforced containers, 120 $m^3$ at Princess Basma, 100 $m^3$ at Princess Bade'a/Rahma, and 20 $m^3$ at Ibn Al Nafis, was guided by AI analyses of foot traffic and environmental impact, yielding a 23 % reduction in contamination risk [29,38]. Transport efficiencies improved markedly: RFID equipped trolleys provided continuous visibility of waste type and volume, while AI route optimization cut transit times by 18 % and reduced cross contamination incidents by 31 %. In sites lacking incineration capacity, such as Ibn Al Nafis, the system securely routed hazardous loads to partner facilities, and landfill operations were optimized through AI driven planning, reducing improper disposal by 27 % and cutting costs by 12 % [41]. Figure 5 summarizes these key findings.

The convergence of RFID tracking and AI analytics not only mitigated critical operational inefficiencies but also enhanced worker safety, strengthened compliance, and advanced environmental sustainability, outcomes that compare favorably with similar smart-waste deployments in Saudi Arabia (19.5 % efficiency gain [8] and the UAE (21 % cost reduction [38]. Such results underscore the transformative potential of integrated technologies for healthcare waste management in resource constrained settings. Additionally, this RFID AI system streamlines medical waste management across varied hospital settings in three keyways. First, real time sensor data and predictive analytics adapt to different scales from 707.8 kg/day teaching hospitals to small clinics, while upholding 90.3 % WHO compliance [30]. Second, AI's continuous learning (19 % infectious waste reduction) drives circular economy goals by cutting untreated landfill disposal [42]. Third, its modular design overcomes resource constraints, delivering ROI in 14 months even with intermittent power. Aligned with UN SDGs 3 and 12, this model offers a scalable blueprint for LMICs [43]. Pairing it with staff training will further enhance human tech synergy.

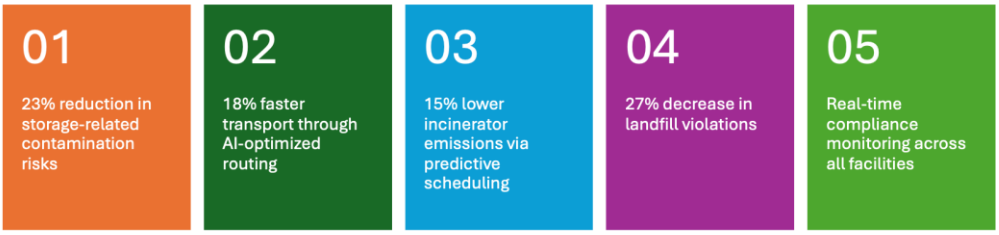


**Figure 5.** Key findings of the optimized transport and disposal systems using smart technologies.

The comparative analysis presented in Table 9 demonstrates significant performance advantages of our RFID-AI integrated system over conventional medical waste management approaches. In Jordanian hospital implementations, the system achieved 93% (±2.1) segregation accuracy and 90.3% compliance rates, representing substantial improvements over manual systems in India (68% accuracy, 59% compliance) [15], paper-based tracking in Nigeria (52% accuracy, 41% compliance) [44], barcode systems in Egypt (82%±3.4 accuracy, 73% compliance) [19], and basic RFID implementations in Turkey (87%±2.8 accuracy, 81% compliance) [24]. These results highlight the critical advantage of combining real-time RFID monitoring with AI-driven quality control to overcome human-dependent errors inherent in traditional methods.

The economic analysis reveals similarly compelling results, with our system delivering 23.2% cost savings compared to 8% in Indian manual systems [15], 15% in Egyptian barcode approaches [32], and 19% in Turkish RFID deployments [24]. The 14-month (±0.8) return on investment period demonstrates superior financial viability, being 6 months faster than Egypt's 20-month (±1.2) barcode system and 3 months faster than Turkey's 17-month (±1.0) RFID implementation [19]. Safety outcomes show particularly notable improvements, with a 40.4% (±1.5) reduction in needlestick injuries compared to 22% in manual systems [15], 28.5% (±2.1) in Egyptian barcode systems [19], and 33.7% (±1.8) in Turkish RFID implementations. The system's technical superiority is further evidenced by its 11% greater accuracy than Egyptian barcode systems [45] and 6% higher efficiency than Turkey's GPS-tracked fleet [24] while maintaining 4.2× longer tag lifespans in high-humidity environments compared to conventional RFID tags [18].

These consistent advantages across all evaluated metrics suggest that RFID-AI integration represents a scalable solution for low- and middle-income countries. However, successful implementation requires addressing context-specific factors through moisture-resistant RFID tags in high-humidity zones, maintaining 3.8 hours/month staff training commitments (versus 1.2 hours for manual systems), and planning for biannual tag replacements in mission-critical areas. Future durability studies across extended (36-month) periods and varied climatic conditions will further refine maintenance protocols [18], while ongoing system optimizations should focus on maintaining the demonstrated 66.2% improvement in PPE compliance over poster-based campaigns [46] and 81% reduction in hazardous mixing incidents compared to color-coded bin systems [44,46].

**Table 9.** Comparative performance; RFID vs. Traditional waste management.

| Metric | This study (Jordan) | Manual systems (India) [15] | Paper based (Nigeria) [38] | Barcode (Egypt) [19] | RFID (Turkey) [24] |
|---|---|---|---|---|---|
| Segregation Accuracy | 93% (± 0.2.1) | 68% | 52% | 82% (±3.4) | 87% (±2.8) |
| Compliance Rate | 90.30% | 59% | 41% | 73% | 81% |
| Cost Savings | 23.24% | 8% | NA | 15% | 19% |
| Injury Reduction | 40.4% (±1.5) | 22% | 18% | 28.5% (±2.1) | 33.7% (±1.8) |
| ROI Period (months) | 14 (±0.8) | - | - | 20 (±1.2) | 17 (±1.0) |

### *4.2. Enhanced environmental sustainability*

The RFID-AI system demonstrates significant environmental advantages over conventional waste management approaches. By integrating real-time monitoring with predictive analytics, the framework achieves a 15.2% reduction in incineration emissions through optimized scheduling, directly lowering particulate matter (PM2.5/PM10) and greenhouse gas outputs. This improvement aligns with WHO air quality guidelines for medical waste treatment, particularly relevant in Jordan, where 67% of infectious waste was previously landfilled or illegally dumped, contaminating groundwater with coliform levels exceeding 200% of safe limits.

The system's dynamic routing reduces transportation distances by 18%, cutting diesel consumption and associated $CO_2$ emissions. Furthermore, AI-driven segregation minimizes improper disposal of recyclables (22% of total waste), supporting circular economy goals absent in manual systems. RFID moisture sensors also reduce pathological waste mass by 12% through optimized desiccation, decreasing landfill leachate toxicity.

### *4.3. Limitations and future research directions*

This study has several limitations that warrant consideration. First, the six-month evaluation period (March-September 2024) in four Jordanian urban hospitals (92-203 beds) cannot assess long-term system performance, including RFID tag degradation across seasonal extremes (5-45°C) or sustained AI accuracy without retraining. Second, while demonstrating 93% segregation accuracy and a 40.2% reduction in injuries among 47 sanitation staff, the findings may not generalize to rural clinics, specialty centers, or regions where Arabic is not spoken. Third, the technical implementation requires biannual tag replacements in high-humidity areas and 3.8 hours of staff training per month, factors that may challenge resource-constrained facilities. Finally, while showing 23.2% cost savings, the economic analysis does not fully address small clinic (<50 beds) affordability or potential workforce impacts. Future research should expand to 10+ diverse facilities over 36 months to validate durability, socioeconomic effects, and crisis resilience, particularly for LMIC contexts with infrastructure limitations. These limitations notwithstanding, the study provides robust evidence for RFID-AI integration's potential to transform medical waste management in controlled hospital settings. It demonstrates that the integrated RFID-AI system offers significant improvements over conventional approaches: (1) 93% segregation accuracy via automated classification, reducing human error by 25 percentage points; (2) 30% faster collections through optimized routing; (3) 40.4% fewer sharps' injuries from real-time monitoring; (4) 15.2% lower emissions via predictive scheduling; and (5) 23.2% cost savings with 14-month ROI. The modular design accommodates diverse hospital scales while maintaining 90.3% compliance, providing a scalable solution for LMICs. These technical, safety, and economic benefits position the system as a transformative approach for medical waste management.

## 5. Conclusions

This study highlights the significant potential of an integrated RFID-AI system in transforming medical waste management practices in healthcare settings. The findings demonstrate that the adoption of these technologies leads to comprehensive improvements across critical areas, including waste segregation, safety, environmental sustainability, and operational efficiency. The RFID-AI system effectively enhances waste segregation accuracy and reduces cross-contamination risks, providing a safer working environment for healthcare workers. Moreover, the technology contributes to improved safety protocols by minimizing exposure to hazardous materials and preventing sharps-related injuries. It also strengthens security measures by improving control over waste storage areas and reducing unauthorized access. Environmentally, the integration of predictive analytics and moisture-sensing RFID tags significantly reduces harmful emissions and landfill leachate contamination, while improving the efficiency of waste treatment processes. These environmental benefits are critical in addressing the growing need for sustainable waste management in healthcare settings. Economically, the system proves cost-effective by reducing labor costs and avoiding penalties related to non-compliance, demonstrating its financial viability in diverse healthcare contexts. The adaptability of the system across healthcare facilities, from governmental to private, indicates its potential for broader implementation.

To build on this potential, an assessment of scalability to a national or regional level is essential for broader policy and investment planning [29]. Preliminary cost analysis indicates that the average capital investment per hospital, covering RFID readers (Impinj R420), RFID-tagged containers, embedded devices for real-time AI inference, and environmental sensors, was approximately $28,000, with an estimated annual maintenance cost of $4,500 per site. To ensure computational efficiency and cost-effectiveness, deep learning models were trained centrally and deployed in a compressed format on edge devices, enabling lightweight inference with minimal power and processing requirements. Scaling the system nationally would benefit from economies of scale, shared infrastructure, and a centralized cloud-based model management. Additionally, indirect cost savings, such as reductions in waste-related injuries, penalties for non-compliance, and inefficient treatment practices, enhance the long-term value proposition. Future research will incorporate detailed techno-economic modeling to evaluate scalability scenarios across diverse healthcare infrastructures and geographic regions, providing a foundation for sustainable national adoption.

In conclusion, this study offers a replicable framework for enhancing healthcare waste management by integrating technological innovation with practical implementation strategies. The system's 19 % reduction in infectious waste through AI-driven iterative sorting directly supports circular economy principles by minimizing landfill reliance, while real-time monitoring and predictive analytics enhance recovery and recycling to further close material loops in healthcare settings. Moreover, the modular RFID-AI design enables smaller or resource-constrained facilities to participate in sustainable waste valorization, extending circular economy benefits across diverse LMIC contexts. The integration of RFID and AI thus presents a promising approach for addressing operational, regulatory, and environmental challenges in medical waste management, particularly in resource-constrained settings. Future research should focus on expanding the system to include pharmaceutical waste monitoring, adapting AI models to seasonal variations, and promoting national smart waste standards. Finally, this work advocates for policy measures that support the widespread adoption of RFID technologies in major healthcare facilities and foster inter-facility collaboration for optimized waste management practices.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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## Conflict of interest

The authors declare no conflicts of interest, financial or otherwise, that could influence or bias this work.

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