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Applications of Robotic Systems and Emerging Technologies in the Collection, Classification, and Treatment of Medical Waste: A Systematic Review

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***Abstract*—The growing volume of infectious medical waste represents a critical challenge for public health and environmental protection, demanding more efficient solutions in hospital waste management (MWM). The contribution of this research is to offer a systematic review of advances in robotic systems and emerging technologies, including artificial intelligence, blockchain, Internet of Things (IoT), and drones applied to the collection, classification, and treatment of medical waste. To do this, a search strategy was used in databases (Scopus, Web of Science, IEEE Xplore, among others) between 2019 and 2024, using keywords related to "medical waste," "robotics," "AI," and "blockchain." After applying inclusion and exclusion criteria, 107 studies were selected that report at least partial validations in health settings. The results show that integrating robotic systems with computer vision and deep learning algorithms can improve classification accuracy by more than 90% while reducing the direct exposure of personnel to infectious material. In addition, technologies such as blockchain and IoT strengthen data traceability and security, although economic and regulatory challenges that limit their large-scale adoption persist. In conclusion, robotics and emerging technologies constitute a promising approach to optimize medical waste management. Even so, greater standardization of performance metrics and validations in high-capacity hospitals are required, as well as the active involvement of health authorities to promote their implementation.**

Keywords*—*Medical Waste; Autonomous Systems; Emerging Technologies; Artificial Intelligence; Blockchain.

I. INTRODUCTION

The need to improve MWM has increased considerably in recent years, driven by the expansion of health services and the diversification of treatments [1], [2]. According to various studies, improper waste disposal poses significant risks to health and the environment, such as the spread of pathogens and chemical contamination [3]. Despite establishing international regulatory frameworks, gaps persist in adopting technological solutions that automate and improve traceability [4]. In this context, the autonomous robotics system (ARS) and the emerging technologies (ET) have emerged as fundamental components for sustainable modernization [5].

In many hospitals, clinical waste management is still a manual process, relying heavily on the experience of workers and exposing them to risks from sharp objects or infectious fluids [6]. This situation increases incident rates and complicates the standardization of processes, particularly when handling high volumes of daily waste [7], [8]. Increased production of disposable materials has led some facilities to invest in new methodologies or equipment, but global adoption of automation remains limited [9]. However, the scientific community and regulators recognize that robotics and AI offer robust and scalable solutions [10].

The COVID-19 pandemic further exposed the vulnerabilities of traditional collection systems, which struggled to manage the increase in personal protective equipment, such as masks and gloves [11]. This highlighted the potential of robots to perform repetitive or dangerous tasks, reducing the exposure of cleaning staff [12], [13]. While several institutions have validated the effectiveness of robotic prototypes, challenges remain in integrating them with hospital infrastructure and ensuring data interoperability [14]. Beyond emergencies, the trend indicates a growing collaboration between humans and machines, complementing skills and improving safety [15].

From a logistical point of view, robotics promises to optimize the internal flow of waste and container transport using autonomous navigation algorithms [16]. In addition, AI enables the automatic sorting of medical waste, leveraging visual recognition and RFID tags to separate infectious material from recyclable waste [17]. However, widespread adoption depends on factors such as implementation costs, hospital setting adaptation, and health authorities' approval [18]. Despite these challenges, numerous reports project positive impacts on productivity and incident reduction through automation [19], [20].

However, there continues to be a lack of systematic reviews that comprehensively address the applicability of autonomous robotics and emerging technologies in medical waste management, considering the technical, economic, and regulatory barriers preventing their broad adoption. The contribution of this research is to analyze recent advances in MWM automation, describing the proposed solutions and the challenges associated with their implementation.

Motivated by these factors, this article presents a comprehensive review of the application of autonomous robotics in MWM, covering concepts, fundamentals, and adoption challenges [21]. It explores enabling technologies, case studies, and future trends that could revolutionize hospital waste management [22]–[25]. The document is organized into seven sections: Introduction (Section I), Fundamentals and Basic Concepts (Section II), State of the Art at MWM (Section III), Technologies and Methods (Section IV), Applications and Case Studies (Section V), Future Challenges and Directions (Section VI), and Conclusions (Section VII).

II. Fundamentals and Basic Concepts

A. Medical Waste Sorting and Protocols

MWM covers the classification, collection, transport, treatment, and final disposal of waste generated in clinical settings, hospitals, and laboratories [26]–[28]. Due to the diversity of materials, ranging from basic inputs such as gauze or syringes to chemical and radioactive substances, international organizations such as the World Health Organization (WHO) and the Pan American Health Organization (PAHO) have established guidelines for categorization. These include infectious, chemical, radioactive, standard waste classifications, and specific color-coded containers [27], [29].

Most national regulations adapt these guidelines to local conditions, outlining requirements for labeling, maximum storage durations, and methods for disinfection or incineration [30], [31]. Handling advanced medical devices or dangerous drugs increases complexity, requiring strict protocols and highly trained personnel [32]. In this context, robotization aims to minimize personnel's direct exposure to medical waste, alleviate manual tasks, and improve the control of biological hazards [33]-[35]. Table I summarizes the key parameters for medical waste sorting and handling requirements, detailing the objects, treatments, and references associated with each type of waste. This classification provides a structured approach to waste management and highlights the diversity of protocols required for different categories of waste.

TABLE I. Medical Waste Sorting and Handling Requirements

Type of waste	Parameters		
	Objects	***Treatment***	***References***
Infectious	Gloves, gases, syringes with liquids.	Disinfection or sterilization (autoclave), red containers	[26], [41], [45], [101]
Pathological	Organic remains, human tissues, laboratory samples	Incineration in septic tanks controlled by special ovens	[27], [28]
Held	Agujas, bisturíes, lancets	Rigid and labelled containers, post-incineration or autoclave	[29], [45]
Chemical	Expired medications, solvents, lab reactions	Chemical neutralization; High-temperature incineration	[27], [101]
Radioactive	Remains of nuclear medicine procedures, radioactive isotopes.	Temporary storage in shielded containers until radioactivity decays	[26], [41]
Common	Household waste such as paper and clean packaging)	Collection with urban waste; possible recycling if uncontaminated	[28], [29], [45]

B. Autonomous Robotic Systems for Waste Management

The ARS is designed to operate in hospital settings with minimal human intervention. These robots integrate mobile chassis, manipulator arms, and sensors (e.g., optical, proximity) with software algorithms for navigation and object identification [36], [37], [42]. ARS's main objectives at MWM are:

- Reducing human contact with infectious waste.
- Systematizing collection.
- improve the traceability of each article [19], [44].

To achieve these goals, the ARS architecture includes subsystems for movement (e.g., motors, wheels, or tracks), control (trajectory planning, force control), and perception (such as RGB cameras and LIDAR sensors) [38]-[40]. Some prototypes in the literature use terrestrial signaling guidance systems, while others employ real-time mapping techniques, such as SLAM (Simultaneous Localization and Mapping) [33], [39]. A recurring challenge lies in adapting to the dynamic corridors of hospitals, where robots must avoid collisions with staff, stretchers, and other medical equipment [49], [54].

C. Emerging Technologies for Waste Management

ET in MWM has created new opportunities to improve efficiency, safety, and traceability in hospital settings. These technologies enable more intelligent decision-making, real-time monitoring, and secure data management. Fig. 1 shows the distribution of publications reporting on AI, IoT, and blockchain applications in MWM. The data shows that AI is the most addressed technology, followed by IoT, while blockchain is discussed in fewer studies. The following sections provide a detailed exploration of individual contributions to these technologies.

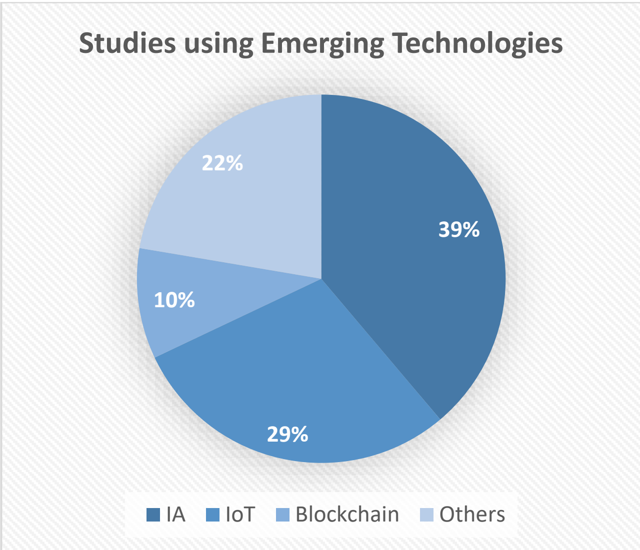

Fig. 1. Distribution of studies that apply AI, IoT and Blockchain in MWM

A continuación, se describe cada una de las tecnologías emergentes:

1) Artificial intelligence: AI applied to waste recognition, and classification employs convolutional neural networks (CNNs) trained on large image datasets, including syringes, gloves, and test tubes [52], [68]. This technology improves the robot's ability to distinguish between visually similar objects, such as different types of plastic, and assign each item to the appropriate container [38]. In addition, some studies integrate deep learning with heuristic algorithms to prioritize hazardous waste collection, providing immediate notifications to staff in cases of container saturation [46], [78].

2) Blockchain: Blockchain facilitates complete traceability of the waste lifecycle by preventing data tampering and recording every interaction (e.g., date, time, responsibility) [42], [64]. Proposed applications include the secure distribution of information between hospitals, waste treatment companies, and regulatory authorities, thereby improving transparency [48], [65].

3) Internet of things: IoT technologies in hospital settings enable environmental sensing (e.g., gas detectors, humidity sensors), allowing robots to assess additional risks (e.g., leaks, spills) and plan safer routes [34], [80]. In addition, real-time connectivity speeds up the automatic upload of collection data to hospital systems, reinforcing document management [82], [88].

III. Styling State of the Art in Medical Waste Management

A. Traditional Methods

Many hospitals maintain manual procedures for the collection, transport, and final disposal of waste [33], [46], [47]. Fig. 2 (inspired by a previous study [33]) illustrates how health personnel use carts or containers to collect waste at each plant without a unified tracking system that provides real-time data on the number of bags collected or their composition [45].

Fig. 2. Staff management of medical waste

This circumstance generates several problems:

- Direct exposure to pathogens (risk of punctures and disease transmission) [8], [9].
- Poor standardization of segregation, with frequent errors in waste classification [6], [7].
- Difficulty meeting collection times under conditions of high demand (e.g., outbreaks) [11], [12].

Although some facilities have adopted semi-automated systems (belts, internal conveyors), final handling tasks are carried out by non-specialist personnel [49], [53]. These limitations have driven the robotization of the waste management process to minimize human contact and improve traceability [5], [19], [44].

B. Automated Systems and Their Degree of Adoption

The deployment of mobile or fixed-arm robots in medical waste management, particularly during the final stages of the waste line, is advancing in research centers and hospital pilot programs [30], [51], [55]. These robots, equipped with proximity sensors and autonomous navigation algorithms, navigate hospital corridors, collect waste bags, and transport them to storage rooms [44]. Some field trials have shown that this approach can reduce total harvesting time by more than 30% [62], [79].

However, widespread adoption faces several barriers, including the need for technical staff to perform maintenance, infrastructure adaptations, and cultural resistance among hospital workers, who may fear job replacement or distrust the reliability of robotic systems [53], [54].

In Fig. 3 (inspired by a previous study [44]), an example of an automated robot called UNESPTroyer is shown; in Fig. 4 (inspired by an earlier study [46]), a voice-controlled, ROS-based robotic arm, also oriented to waste management; and in Fig. 5 (inspired by a previous study [87]), an automated guided vehicle for hospital functions. Each integrates proximity sensors and cameras for bag detection and adapted gripping and carrying methods.

Fig. 3. UNESPTroyer Waste Management Robot

Fig. 4. Voice-controlled, ROS-based robotic arm

Fig. 5. AGV automated guided vehicle applied to hospital environments

C. Emerging Technologies and Edge Computing

Improved robotic handling using flexible grippers (soft robotics) makes it possible to hold bags without breaking them and to handle fragile or sharp objects. In Fig. 6 (inspired by a previous study [74]), two gripping approaches (suction and compressed air) that facilitate safe handling are illustrated. In addition, multispectral vision helps differentiate materials based on their optical signature, achieving classification accuracies of over 90% [56]–[59].

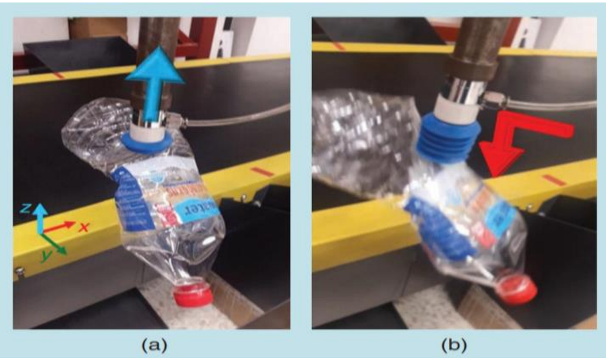

Fig. 6. Waste handling by (a) suction and (b) compressed air

Edge computing also minimizes latency in detection and decision-making, which is critical when an immediate response is required to risk situations, such as the rupture of a bag with infectious fluids [58], [60].

D. Common Mistakes in MWM

One of MWM's main objectives is to achieve full traceability, ensuring that each waste is linked to the patient or procedure that generated it and that its journey to final disposal is transparent [61], [63]. Robots must be integrated with the Hospital Information System (HIS) and specialized databases to achieve this. Protocols such as HL7 and FHIR facilitate this data sharing [104], [105], but many hospitals still lack a robust digital infrastructure to support these integrations.

In addition, cybersecurity is a critical concern. A cyberattack could disrupt waste logistics or compromise sensitive patient data, emphasizing the need for secure communication channels and robust data protection mechanisms [48], [64], [84]. Table II summarizes the studies that explore integrating robotic systems with HIS platforms, highlighting the different degrees of success and the challenges encountered. This table provides a comparative view of how hospitals implement robotic systems and the levels of interoperability achieved.

TABLE II. INTEGRATION OF ROBOTIC SYSTEMS WITH THEIR PLATFORMS IN DIFFERENT STUDIOS

Ref	**Integration with HIS platforms**		
	Type of interoperability	***Level of integration***	***Main findings***
[48]	HL7 protocols for the exchange	Partial (volume logging only)	The platform allows the time and amount of waste the robot collects to be recorded, but it does not integrate saturation notifications or real-time routes.
[62]	FHIR to interoperate with HIS	Moderate (pick-up routes and alerts)	The robot downloads the assigned routes according to the location of the saturated containers, feeding the hospital's database with the exact time and type of waste, which is a key factor for traceability.
[76]	API Ownership + IoT Plugin	Advanced (bi-directional update)	The robot automatically updates the waste database, and the HIS alerts the cleaning staff when anomalies (excess infectious waste in an area) are detected. Improves coordination.
[85]	Blockchain for traceability	Partial (immutable storage only)	Integration focused on recording interactions (collection, transport) in an immutable way. It does not implement real-time notifications, but it strengthens security and prevents the manipulation of historical data.
[64], [65]	Mixed piloting (cloud + HL7)	Basic (post-process registration only)	The robot's information is massively uploaded to the hospital system at the end of each day. There are no real-time updates, but it allows audits for historical control of waste streams.

IV. TECHNOLOGIES AND METHODS

A. Robotic Systems and Mechanisms

Robots designed for MWM require mobile bases capable of safely navigating hospital corridors, employing sensors such as LIDAR or 3D cameras for simultaneous mapping of the environment [62], [71]. The choice of locomotion systems, whether wheels or omnidirectional tracks, depends on the hospital's infrastructure and the need to navigate ramps or uneven surfaces [72]. Some studies describe manipulator arms or grippers specifically adapted to handle bags without breaking them, incorporating antimicrobial surfaces to improve hygiene [46], [73], [74]. Route control algorithms are often integrated to avoid collisions and enable efficient operation in congested clinical environments [76]. In addition, specific prototypes allow switching between teleoperation and autonomy, depending on the task's criticality, minimizing personnel's exposure to hazardous waste [90].

B. *Perception and Machine Vision*

Machine vision is vital in identifying and sorting medical waste by analyzing shapes, colors, and textures [75]. Implementations frequently use RGB cameras and depth sensors to reconstruct 3D models of bags or containers, even in difficult lighting conditions [77]. In addition, multispectral vision has been adopted in some prototypes to improve the differentiation of plastics, metals, and biomedical materials [78]. Combining visual data with RFID signals or proximity sensors (infrared, ultrasound) is standard to improve accuracy in highly heterogeneous environments [79]. This approach is reinforced by adaptive control mechanisms that adjust force and movement, prevent spillage, and ensure safe handling [80].

C. *Artificial Intelligence and Learning*

AI plays a key role in the sorting of medical waste. Numerous studies have investigated deep learning techniques, notably CNNs, trained on extensive datasets comprising images of syringes, gloves, and other hospital waste [81], [84]. AI allows robots to identify mixed or partially obscured objects accurately, achieving more than 90% accuracy in controlled environments [68]. In addition, expert systems and fuzzy logic models have been explored to prioritize waste collection based on its level of biohazard [82]. Since these networks operate in real-time, studies emphasize the need for robustness in the face of changes in lighting conditions or unexpected breakage of waste bags [83]. In addition, some research highlights the importance of regularly updating AI models to address new variants of waste or changes in hospital protocols [85]. Fig. 7 (inspired by a previous study [74]) illustrates an example of material classification using Mask R-CNN, where objects are segmented and highlighted with random colors.

Fig. 7. Material sorting using R-CNN mask where the colors of different debris are randomly selected

D. *Internet of Things and Real-Time Connectivity*

IoT facilitates seamless communication between robots and environmental sensors (e.g., gas detectors and temperature monitors), enabling the detection of risks such as spills or container saturation [83], [86]. When abnormal conditions are detected, the software can replan routes or trigger alerts for personnel [87]. Real-time connectivity also allows for coordinating multiple robotic units, enabling efficient collaboration in large hospital environments [88].

Some studies propose AI-assisted teleoperation, where human personnel monitor critical events while autonomous systems take over routine tasks [89]. It is suggested that encryption and authentication protocols be implemented to protect these networks and prevent unauthorized access [83], [92].

E. *Blockchain and Cybersecurity*

Cybersecurity is a key aspect of medical waste management, as network attacks could compromise waste logistics or expose sensitive patient data and information about infectious waste [84]. Blockchain technology has been proposed as an immutable record method that bolsters traceability by preventing alterations to collection histories [42], [48], [92]. Through the blockchain, every interaction, such as the time of collection, the identification of waste, and the route followed, is recorded in a block, ensuring the integrity of the data and preventing retroactive manipulation [85]. However, implementing blockchain in hospitals presents scalability and performance challenges, as the infrastructure must process transactions efficiently and maintain reliable participating nodes [98].

F. *Collaborative Robotics*

Collaborative robots have emerged as a solution to address cultural resistance among staff. These robots allow close interaction with humans through integrated safety features such as force sensors and stereoscopic vision [106], [107]. These cobots learn gesture patterns or respond to verbal commands, cooperating with nursing and cleaning staff without needing protective enclosures [93]. From a practical perspective, some research prioritizes early detection of damaged bags and sealing leaks, while other work focuses on achieving full traceability of containers through blockchain and AI integration [94]–[96].

Trials in real-world scenarios significantly reduce harvesting times and occupational exposure risks [99]. However, studies emphasize the importance of maintenance plans and software updates to adapt to continuous technological improvements [97], [100]. In addition, the research highlights the ecological dimension of robotic systems, analyzing their carbon footprint compared to manual methods to encourage more sustainable practices in the future [101]–[103].

G. *Methodology for the Review and Classification of Works*

To conduct this review, the following databases were consulted: Scopus, Web of Science (WoS), IEEE Xplore, SpringerLink, MDPI, PubMed, and Google Scholar. The search focused on studies related to "robotics," "artificial intelligence," "IoT," "blockchain," "hospital automation," and "medical waste." Both journal articles and indexed conference proceedings were analyzed, giving priority to papers that included partial or complete validations in healthcare settings.

As part of the strategy, a filtering process was carried out:

1) Keywords: ("medical waste" OR "healthcare waste") AND ("robot*" or "autonomous system*" or "AI" or "IoT" or "blockchain").

2) Inclusion criteria: Publications in English or Spanish addressing a technological approach to medical waste management.

3) Exclusion criteria: Articles that are merely descriptive without innovation, duplicates, or focused on non-clinical residues.

After examining titles, abstracts, and sections of interest, a final corpus of 107 articles was selected. They were classified into seven categories (1–7) according to their primary focus (Robotics, AI, IoT, Blockchain, Health 4.0, COVID-19, and others). Table III summarizes the number of studies and their references, providing an organized view of research in this field.

TABLE III. CLASSIFICATION OF THE ARTICLES FOUND IN THE SYSTEMATIC REVIEW

Category	**Data**		
	Spotlight	***Number of articles***	***References***
1	Robotics for medical waste	11	[3], [5], [7], [12], [19], [26], [33], [44], [46], [74], [87]
2	AI/Machine Learning Applied to Waste (Deep Learning, etc.)	12	[16], [18], [21], [23], [28], [29], [30], [47], [50], [52], [100], [101]
3	IoT/Automation in Medical Waste (Sensors, Communication, Technology, T, Smart Container, etc.)	14	[11], [31], [32], [34], [35], [39], [42], [49], [51], [53], [90], [96], [97], [102]
4	Blockchain and Supply Chain for Waste/Medical Equipment	6	[48], [79], [81], [83], [88], [92]
5	Healthcare 4.0 / Digital Transformation in Healthcare (Industry 4.0, Hospital Management)	6	[1], [2], [4], [8], [36], [93]
6	COVID-19 and medical waste management	16	[9], [10], [22], [27], [37], [38], [40], [43], [62], [77], [85], [86], [91], [94], [98], [103]
7	Other references (not classified in A-F: general robotics, AI subtopics, logistics, sustainability)	38	[6], [13], [14], [15], [17], [20], [24], [25], [41], [45], [54], [55], [56], [57], [58], [59], [60], [61], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [75], [76], [78], [80], [82], [84], [89], [95], [99], [104], [105], [106], [107]

V. APPLICATIONS AND CASE STUDIES

A. *Hospital Implementation*

Several hospitals have deployed or tested mobile robots to collect waste bags at different locations and transport them to centralized collection rooms, freeing staff from repetitive and dangerous tasks [62], [87], [100]. The main findings of these implementations state:

- Decreased contact with infectious fluids, reducing puncture incidents by approximately 20-40%, according to field reports [79], [84].
- Up to 30% less pick-up time, thanks to route optimization and scheduling [5], [51].
- Digital traceability of each bag through automated registration in the hospital system, allowing for more accurate audits [42], [65].

However, limitations were observed when adapting automated guided industrial vehicles (AGVs) to hospital environments, such as narrow corridors and inadequate elevators [20], [34]. In contrast, hospitals with greater digital maturity successfully integrate robot-generated data into their HIS, allowing detailed documentation and statistical analysis of incidents [48], [61]. This shows that successful adoption depends not only on the technology infrastructure but also on the attitude of the staff towards collaboration with automated systems.

B. *Laboratories and Research Centers*

At the experimental level, several prototypes have been validated in laboratories simulating mixed waste scenarios (e.g., syringes, test tubes, gloves). These experiments measure the accuracy of recognition, with some designs incorporating multispectral sensors or depth cameras to achieve detection rates of up to 95% for infectious residues [46], [57], [59], [68]. Laboratories provide a controlled environment for fine-tuning classification algorithms, including deep learning and computer vision, and testing the robustness of robotic manipulations [28], [74]. These experimental validations often serve as critical steps for developing pilot prototypes or initiating partial implementations in real-world hospital settings.

C. *Comparison of Robotic Solutions*

Comparing different robotic solutions for medical waste management requires evaluating factors such as the type of robot (AGV, mobile robot, fixed arm), navigation method (SLAM, physical guides), level of autonomy, and performance metrics (e.g., sorting accuracy, incident reduction). Several authors [44], [46], [87], [3], [19] describe hardware architectures and AI or control algorithms, enabling comparative tables that show the advantages, disadvantages, and estimated costs of each proposal. Table IV presents a comprehensive comparison of robotic systems used in medical waste management. The table highlights key features, including navigation methods, autonomy levels, and performance metrics, offering a clear view of each system's strengths and limitations. This information is a valuable reference for selecting or designing robots tailored to the hospital's specific requirements.

TABLE IV. COMPARISON OF ROBOTS FOR MEDICAL WASTE

Ref	Topics					
	Platform	***Locomotion***	***Classification accuracy***	***Environment (laboratory/hospital)***	***Advantages***	***Limitation***
[44]	LEGO Arm Mobile Robot	Single wheels	70-80% (controlled environment)	Laboratory	Low cost, easy prototyping, suitable for teaching and research	Limited to smooth surfaces, not ideal for heavy loads
[46]	Robotic arm YOLOv3	Fixed arm (without base)	85-90% in type detection	Laboratory Simulations	Robust AI to recognize syringes and gloves, ROS integration	Mobility was not included; Requires personnel to move sorted waste
[87]	Hospital semiautónomo AGV	Optical Guidance System	N/A (no classification)	Hospital	Transports large volumes of waste, reduces staff exposure in aisles	Depends on floor guidelines, little adaptability to changes in the hospital's layout
[3]	Autonomous "indoor" robot (concept.)	Omnidirectional wheels	90% (AI prototype)	Laboratory (testing)	The high degree of autonomy, obstacle detection, and initial bag sorting	Not yet validated in a real hospital, mechanical strength not evaluated
[19]	Prototype with SLAM + light arm	Wheels with LIDAR	88-95% (in experiments)	Laboratory Simulation	Precise navigation in complex environments, integration of SLAM and vision neural networks	Continuous calibrations and lighting problems are required in brightly lit or glare areas.

VI. DISCUSSION AND LIMITATIONS

A. Technical Limitations

1) Robustness and maintenance: Robots deployed in hospital environments must withstand shocks, exposure to fluids, and areas of high contamination. This requires airtight housings, sterilizable components, and antimicrobial coatings, introducing complexities into the design and integration of delicate sensors.

2) Sensory calibration: Lighting variations, reflective surfaces in trash bags, and overlapping objects can confuse machine vision systems. These challenges require frequent calibration of cameras and adjustments to vision algorithms to maintain accuracy.

3) Multi-robot scalability: Coordinating multiple robots in large hospitals, especially shared spaces such as hallways and elevators, requires advanced fleet management and collision prediction algorithms. Scaling up is further hampered by inadequate infrastructure, such as narrow corridors and network limitations, making large-scale deployments difficult.

B. Implementation Challenges

1) Certifications and regulations: Many regions lack specific guidelines for approving robots designed to handle infectious waste. This absence of standards complicates their formal adoption in hospitals, delaying certification processes and creating legal uncertainty about liability in the event of malfunctions [6], [7], [104], [105].

2) Adoption cost: While robotization reduces accidents and improves operational efficiency, the initial investment in hardware, charging infrastructure, and staff training is often high [10], [14]. The long-term profitability of these systems depends on factors such as the daily volume of waste and the local cost of labor.

3) Resistance to change: Human acceptance remains a critical factor. Personnel unfamiliar with the robots operating in the hallways may show reluctance unless proper training and backup protocols are provided. In addition, contingency plans for robot malfunctions are essential to ensure smooth operation and build trust among staff.

C. Research Opportunities

1) Soft robotics: Flexible grippers inspired by soft materials allow for safer handling of fragile bags and containers, reducing the risk of breakage [21], [22], [56]. Validation of these grippers in real-world scenarios offers potential safety improvements and minimizes the force exerted on waste during handling.

2) Coordination with drones: UAV-UGV frameworks have been proposed to transport waste in hard-to-reach areas or situations that require speed, as highlighted in [12]. However, large-scale validations are still in their infancy, presenting research opportunities in developing airport logistics for efficient waste management.

3) IA explainable: Neural networks capable of providing "explanations" for their decisions, such as classifying an object as infectious, can improve staff confidence in automated systems [24], 27], [36]. This transparency becomes especially critical in extreme situations, such as handling bags with mixed contents.

4) Embedded systems: The convergence of AI, IoT, blockchain, and robotics fosters safer and more transparent hospital environments [42], [64], [85]. However, this also presents challenges regarding interoperability and standardization, given the heterogeneity of hospital ecosystems and their stringent cybersecurity requirements.

D. Future Trends

1) Hospital 4.0: An ecosystem is projected where robots, sensors, and medical records are synchronized in real-time, extending automation beyond waste management [38], [62]. This requires robust networks, integrated databases, and protocols that link logistical and clinical tasks.

2) Evaluation standards: There is growing interest in establishing standardized metrics of efficacy, safety, and cost-effectiveness, facilitating comparison between solutions from various manufacturers [66], [70], [79]. These standards are vital to legitimize investments and guide institutional purchasing decisions with objective criteria.

3) Sustainability: Robotization is increasingly analyzed from an environmental perspective, considering carbon footprint and resource use. Studies indicate that incident reduction and route optimization can compensate for energy consumption [45], [101], [102]. This approach emphasizes the dual benefit of automation, addressing health and ecological concerns.

VII. Conclusion

This review, based on the analysis of 107 articles, confirms that robotization and emerging technologies (AI, IoT, blockchain, soft robotics) are transforming medical waste management. Notable progress includes reducing staff exposure to infectious material and improving operational traceability, contributing to a safer clinical environment. However, technical limitations (robot robustness, sterilization requirements), regulatory gaps (lack of clear certifications), and high upfront costs hinder mass adoption.

Current trends indicate a convergence of innovative approaches: on the one hand, soft robotics and explainable AI promise to optimize system accuracy and user acceptance; on the other, coordination with drones and IoT interoperability drives progress towards a Hospital 4.0. Likewise, cybersecurity and blockchain technologies are emerging as pillars to guarantee the immutability and protection of data in critical systems. The ecological impact of these advances should not be underestimated since reducing incidents and optimizing routes can generate significant environmental benefits in the medium term.

In conclusion, automation in medical waste management represents more than a technical advance; It implies a paradigm shift that requires collaboration between engineers, clinical specialists, regulatory authorities, and hospital staff. Success will require a multidisciplinary approach integrating sustainability, public health protection, and effective modernization of hospital processes.

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