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Advancing Sustainable Medical Waste Management: A Case Study on Waste Generation and Classification in a University Hospital Microbiology Laboratory

Ender Çetin [1], Ahmad Hussein [1] and Sevgi Güneş-Durak [2,*]

[1] Department of Environmental Engineering, Faculty of Engineering, Istanbul University-Cerrahpaşa, 34320 Istanbul, Türkiye; ecetin@iuc.edu.tr (E.Ç.)
[2] Department of Environmental Engineering, Faculty of Engineering-Architecture, Nevsehir Haci Bektas Veli University, 50300 Nevsehir, Türkiye
* Correspondence: sgdurak@nevsehir.edu.tr

Abstract: Effective medical waste management is crucial for minimizing environmental contamination, protecting occupational health, and advancing sustainability goals in healthcare systems. However, microbiology laboratories remain underexplored in waste characterization studies, despite their potential to contribute to sustainable healthcare operations. This study assessed waste generation patterns, classification accuracy, and the impact of training on regulatory compliance in a university hospital microbiology laboratory. Over 45 days, waste from six specialized units was categorized and weighed daily. A survey of 304 healthcare professionals evaluated their knowledge of medical waste handling. Statistical analyses revealed that training frequency ($R^2 = 0.72$, $p < 0.01$) was the most significant predictor of compliance, while years of experience had no measurable impact. On average, the laboratory generated 22.78 kg/day of medical waste, 11.67 kg/day of liquid waste, and 5.61 kg/day of sharps waste, with the bacteriology unit being the largest contributor. Despite adequate general awareness, 15% of staff misclassified hazardous waste—particularly expired pharmaceuticals and cytotoxic vials—indicating critical gaps in practice. The findings support the need for recurring training programs, stricter monitoring systems, improved waste labeling, and the integration of digital tracking tools. These interventions can reduce environmental burdens, enhance healthcare sustainability, and support the development of more resilient waste management systems in medical institutions. Future research should explore how AI and automation can further strengthen sustainable healthcare waste strategies.

Keywords: sustainable healthcare; medical waste management; environmental sustainability; waste classification; hospital microbiology laboratory

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1. Introduction

Medical waste management plays a vital role in hospital operations, significantly influencing both environmental sustainability and occupational safety. While general hospital waste has been widely studied, microbiology laboratories remain understudied despite their production of highly hazardous waste—including infectious, chemical, and sharps materials [1].

The incorrect classification and disposal of expired pharmaceuticals, fluorescent lamps, cytotoxic drugs, and personal protective equipment (PPE) continue to pose serious risks to public health and the environment. The World Health Organization (WHO) estimates that

approximately 15% of healthcare waste is hazardous and requires specialized handling [2]. Misclassification leads not only to improper disposal but also increases the potential for cross-infection, injuries, and environmental contamination [3,4].

Although healthcare professionals may possess theoretical knowledge, studies suggest that actual practices do not always align with guidelines. Research indicates that the frequency of training is a stronger predictor of accurate waste segregation than years of experience [5,6]. Inconsistencies in waste classification are frequently linked to inadequate training, high workloads, lack of systematic monitoring, and ambiguously implemented protocols [7].

Multiple researchers have emphasized the importance of continuous education, clear color-coded segregation systems, and standardized procedures. Sapkota et al. (2014) demonstrated that color-coded approaches are associated with improved waste handling and reduced classification errors [8]. Similarly, Ruoyan et al. (2010) and Ferreira et al. (2024) reported that comprehensive and recurring training significantly enhances classification accuracy [9,10]. Ferreira et al. (2024) further advocate for sustainable education to ensure up-to-date knowledge and reduced infection and pollution risks [10]. Letho et al. (2021) highlighted a disconnect between healthcare workers' awareness and their actual clinical practices, attributing this to weak protocol compliance [11]. Janik et al. (2023) emphasized that the mismanagement and misclassification of medical waste can lead to needlestick injuries and cross-infection risks [12].

Additional challenges arise from the evolving nature of waste streams generated by medical procedures and the inconsistent enforcement of regulatory standards. Srivastava et al. (2024) found that the complexity of infectious and chemical waste makes segregation more difficult without clear and consistently applied guidelines [13]. Organizational and systemic barriers, such as poor infrastructure and weak administrative oversight, further exacerbate classification errors. Fuzi et al. (2025) and Raj et al. (2024) reported that these issues contribute to ineffective waste practices, with Raj et al. identifying a triad of obstacles: improper sorting at the source, waste handling inefficiencies, and poor human resource management [14,15].

This study aims to identify and address critical issues in medical waste management by systematically analyzing waste generation patterns, evaluating classification accuracy, and assessing the effectiveness of training programs in a university hospital microbiology laboratory. The key objective is to pinpoint prevalent misclassification practices and training gaps, thereby proposing targeted interventions—including enhanced training programs, stricter monitoring mechanisms, and optimized waste disposal strategies—to improve regulatory compliance, occupational safety, and environmental sustainability. Given that the existing literature predominantly covers challenges in regions such as South Asia and Sub-Saharan Africa, this research further seeks to fill the comparative data gap by focusing specifically on a prominent university hospital in Türkiye, thus contributing valuable insights applicable to similar European healthcare contexts.

2. Materials and Methods

2.1. Description of Medical Microbiology Laboratory

The medical microbiology laboratory is located in a 1306-bed university hospital in the Fatih district of Istanbul. The hospital occupies 170 decares of land and includes one temporary medical waste storage area. This hospital was selected for the study because it is one of the largest public healthcare institutions in Türkiye, serving a densely populated urban region. The medical microbiology laboratory consists of six specialized units: bacteriology, serology, parasitology, mycology, tuberculosis, and molecular diagnostics.

Each unit generates different types of waste depending on the procedures performed:

- ELISA (Enzyme-Linked Immunosorbent Assay) unit: Test tubes and sample bottles containing biological materials and chemical reagents are disposed of as infectious and chemical waste. Additionally, residual chemical liquids from the analyzer are collected in a dedicated liquid waste container.
- Bacteriology unit: Used culture media, Petri dishes, inoculation loops, and contaminated swabs are discarded as infectious waste.
- Parasitology and mycology units: Microscope slides, coverslips, and staining reagents generate both infectious and chemical waste.
- Tuberculosis unit: Produces high-risk infectious waste, including sputum collection containers, NaOH–NALC processing reagents, and single-use personal protective equipment (PPE).
- Molecular diagnostics unit: Generates infectious waste such as used pipette tips, PCR tubes, and gloves contaminated with nucleic acid samples.
- Distilled water, when uncontaminated and used for rinsing instruments or pipette tips, is safely discharged into the sewage system in accordance with hospital protocols.

Additional specific waste types generated in the laboratory include the following:

- Expired medicines: Classified as pharmaceutical waste, these are collected separately and disposed of through licensed hazardous waste disposal facilities.
- Fluorescent lamp waste: Classified as hazardous waste due to the mercury content, collected separately in accordance with hazardous waste management protocols, and sent to specialized recycling or disposal facilities.
- Printer and cartridge waste: Toner cartridges and printer waste are classified as electronic waste and are separately collected, stored, and recycled according to electronic waste disposal regulations.
- PPE waste: Personal protective equipment (PPE), especially from the tuberculosis and molecular diagnostics units, is classified as infectious waste and disposed of following strict infectious waste management guidelines.
- Genotoxic–cytotoxic pharmaceutical waste: These highly hazardous materials are classified separately and collected in dedicated containers, then handled and disposed of through specialized hazardous waste treatment and disposal methods.
- Liquid hazardous waste: Generated from laboratory processes such as Gram staining procedures, these are collected in designated containers separated from the sewage system and delivered to licensed hazardous waste disposal facilities by authorized transporters.

The laboratory operates 24/7, with personnel working most intensively between 09:00 and 16:00. Two staff members are responsible for waste handling and rotate shifts. As medical waste bins become full, the bags are sealed, labeled, and transferred to the institution's 40 m^2 temporary medical waste storage area. Here, the waste is weighed, recorded, and stacked in an orderly manner without compression or breakage until collection.

Medical waste is collected daily by Istanbul Environmental Management Industry and Trade Inc. (ISTAC) and transported to the disposal facility. Chemical liquid waste is stored in labeled liquid waste containers according to the Waste Management Regulation [16] and is delivered to a licensed hazardous waste disposal facility by an authorized transporter. Notably, the sink where Gram staining is performed in the medical microbiology laboratory has been disconnected from the sewage system, and the liquid waste generated during this process is collected in special waste bins. Domestic waste and recyclable materials—such as clean paper, cardboard, plastic reagent containers, and uncontaminated packaging—are also collected separately, stored in the temporary waste storage area, and sent to the appropriate disposal or recycling facilities.

All waste handling processes are conducted in accordance with national medical waste regulations and the hospital's internal protocols, ensuring both occupational safety and environmental compliance.

2.2. Survey Study

2.2.1. The Place and Time of the Study

This descriptive, observational, and cross-sectional study was conducted at Istanbul University Cerrahpaşa Medical Faculty Hospital located in the Fatih district of Istanbul province. During this research, face-to-face interviews were conducted with healthcare workers, and a questionnaire on medical waste was administered. Data were obtained in line with the answers given by the participants to the questions specified in the questionnaire form. The data were collected between 25 March 2022 and 21 May 2022.

2.2.2. The Population and Sample of the Study

The population of this study consists of all healthcare professionals working at Istanbul University Cerrahpaşa Hospital in the Fatih district of Istanbul. The sample of this study consists of 304 healthcare professionals who participated on a voluntary basis and were informed about the investigation. The distribution of the participants according to their work units is as follows: internal sciences (98 people), surgical sciences (78 people), laboratory (55 people), and other units (56 people).

2.2.3. Data Collection Tools

A "questionnaire form" was used as a data collection tool in this study. The questionnaire form consists of 36 questions grouped into 2 sections:

- Questions related to demographic variables (age, gender, education level, which department they work in, how many years they have been working, etc.) of the participating healthcare professionals;
- Questions to analyze the level of knowledge about the management of medical wastes, hazardous wastes, and laboratory wastes.

The questionnaire took 10–15 min to complete. The researcher had all participants fill out the questionnaire one-on-one in order to ensure that they did not affect each other's answers and to answer questions when necessary.

2.2.4. Evaluation of Data

The demographic information, units of employment, and education levels of the employees were analyzed to identify any statistical differences between their knowledge levels. The raw data obtained through the questionnaires completed by personnel were transferred to a computer, and the SPSS 22.0 (Statistical Package for the Social Sciences) program was used to address the main research questions. Values are shown in tables for visual convenience.

2.2.5. A Limitation of the Study

A limitation of this study is that it was conducted in one location: the Istanbul University Cerrahpaşa Medical Faculty Hospital located in the Fatih district of Istanbul province. Thus, the results may not be generalizable to other populations.

2.2.6. Statistical Methods Used in the Study

The statistical methods used in the study, the types of data used, and the purposes of using these methods are given in Table 1.

Table 1. Statistical methods used in the study.

Statistical Method	Data Types Used	Objective
Descriptive statistics	Waste types, employee demographics	Determine overall averages
Correlation analysis	Age, length of employment, education, awareness	Analyze relationships between variables
Regression analysis	Frequency of training, waste management compliance	Analyze relationships between variables
Chi-square (χ^2) analysis	Gender, age, education, misclassification	Test relationships between categorical variables
Reliability analysis (Cronbach's Alpha)	Survey questions	Determine internal consistency of scale

2.3. Hypotheses

2.3.1. Main Hypotheses

H1: *A higher education level and training frequency significantly increase healthcare workers' knowledge of and compliance with medical waste management protocols.*

H2: *The duration of employment alone does not increase the accuracy of medical waste classification.*

H3: *Waste management in the microbiology laboratory is subject to more misclassification than general hospital waste management.*

H4: *The rate of misclassification of waste types can be reduced through special education programs.*

H5: *The misclassification of hazardous waste increases the occupational risks to health workers.*

2.3.2. Sub-Hypotheses

H6: *Younger health workers have more up-to-date knowledge of medical waste management regulations.*

H7: *Health workers with higher levels of education make more accurate decisions about waste classification.*

H8: *The amount of waste generated in the bacteriology unit is significantly higher than in other laboratory units.*

H9: *The misclassification of medical waste leads to increased environmental contamination and increased public health risks.*

H10: *Mandatory and regular training programs are an important factor in increasing compliance with medical waste management protocols.*

3. Results

3.1. Waste Classification

In this study, the types of waste (medical, domestic, packaging, sharps, and liquid waste) and the collection and storage of waste generated in the medical microbiology laboratory of a university hospital were investigated on-site (Figure 1). The color coding in this figure is based on the Turkish Regulation on the Control of Medical Wastes [16], which prescribes red for infectious medical waste, yellow for sharps, black for domestic waste,

and blue for packaging materials. Liquid waste is collected in clearly labeled containers in accordance with institutional protocols.

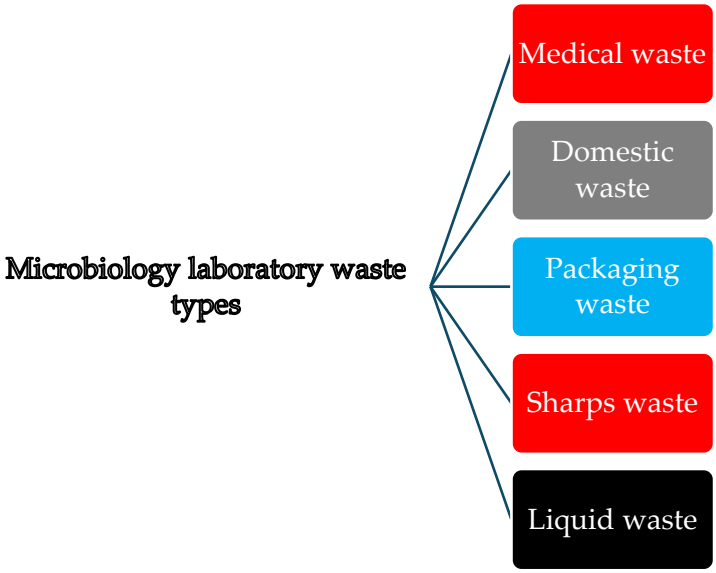


Figure 1. Waste categories in the microbiology laboratory.

Waste generation in six units of the medical microbiology laboratory (bacteriology, serology, parasitology, mycology, molecular, and tuberculosis) was examined, and it was determined that waste is separated according to type. In the bacteriology unit, after culture studies, samples are classified as medical, sharps, and pathological waste and disposed of appropriately. In addition, chemicals used during Gram staining are collected in the liquid waste bin, while glass tubes are sterilized, disinfected, and reused.

An Investigation of the Characterization and Amount of Wastes Generated in the Laboratory

Medical, household, packaging, and liquid laboratory wastes generated in the units were weighed daily for 45 days to characterize and quantify waste from the medical microbiology laboratory. The results of the average 45-day weighing of medical, sharps, domestic, liquid, and packaging wastes generated in the laboratory are shown in Figure 2. Figure 2 shows the average daily amounts and percentages of waste generated in the medical microbiology laboratory. The findings highlight significant challenges in medical waste management, including incorrect segregation, inadequate infrastructure, and inconsistent adherence to disposal protocols. Over a 45-day period, the laboratory produced an average of 22.78 kg/day of medical waste (50.93%), 11.67 kg/day of liquid waste (26.09%), 1.25 kg/day of sharps waste (2.79%), 5.61 kg/day of domestic waste (12.54%), and 3.42 kg/day of packaging waste (7.65%), demonstrating the substantial risks associated with improper waste handling [2,3,17,18].

In addition to reporting the absolute waste generation rates, it is important to contextualize these values in relation to the hospital's operational capacity. The studied university hospital has a capacity of 1306 beds and serves a large urban population, which directly influences the volume of medical waste produced. Based on this capacity, the microbiology laboratory's medical waste generation corresponds to approximately 17.44 g/bed/day, liquid waste to 8.93 g/bed/day, and sharps waste to 4.29 g/bed/day. These normalized indicators allow for better comparisons across institutions and can guide scalable waste management strategies.

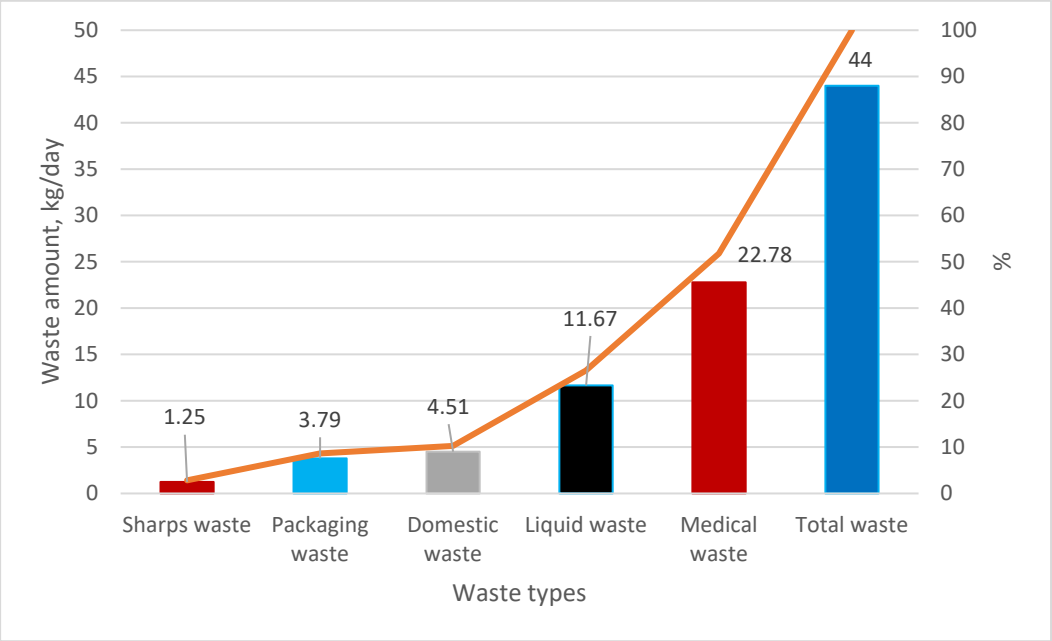


Figure 2. The average daily waste distribution in the microbiology laboratory.

3.2. Statistical Analyses

According to the number of participants and their answers, Cronbach's Alpha coefficient, which reflects the reliability of the study, was calculated as 0.616, which indicates that the internal consistency of the scale is between poor and acceptable. Generally, values of 0.70 and above indicate good internal consistency, while values between 0.60 and 0.70 are considered low but acceptable. To increase the reliability of the scale, the items were grouped under the following titles: medical waste education and knowledge level, waste types and pollution perception, and the impact of medical waste on human health and risk perception.

A total of 304 people participated in this study. Of these, 294 answered questions about gender, 300 about age, 302 about education, 293 about length of employment, and 285 about the department (Figure 3). Of the respondents, 31.7% were male and 60.5% were female. A total of 31% were between the ages of 40 and 50 years, 25.1% were between 20 and 30 years, 22.9% were between 30 and 40 years, 14.1% were 50 years or over, and 0.9% were 20 years or under (Figure 4). A total of 42% of the participants had a bachelor's degree, 31.7% were primary school–high school graduates, 11.9% had an associate's degree, 7.2% had a master's degree, and 1.9% had a PhD (Figure 5). A total of 24.8% of the employees had been working for 0–5 years, 22.6% for 20 years or more, 21.3% for 10–15 years, 12.9% for 15–20 years, and 10.3% for 5–10 years (Figure 6).

The distributions of participants' gender, age, education level, length of employment, and department had standard deviations of 0.476, 1.059, 1.078, 1.524, and 5.917, respectively. This shows that the gender distribution is balanced, and the ages of the participants are very close to each other. The results also show that the participants have similar education levels and that the majority are clustered at one education level (bachelor's degree). The standard deviation of the participants' length of employment shows that some of the participants are new employees (between 0 and 5 years), while others are more experienced (20 years or more). In addition, the work department has a standard deviation of 5.917, which indicates that the respondents work in very different departments.

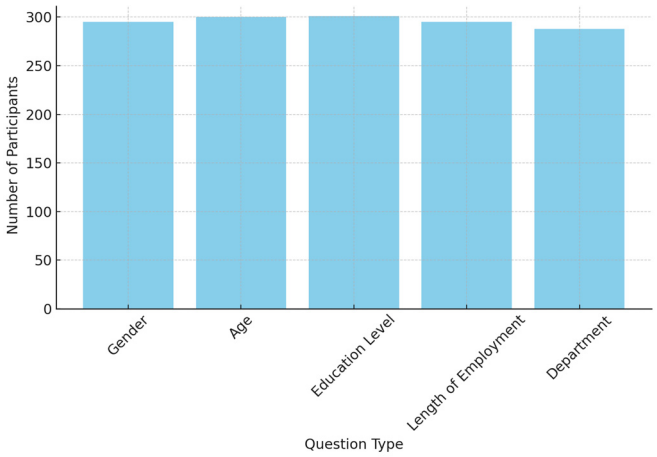


Figure 3. Number of participants by question type.

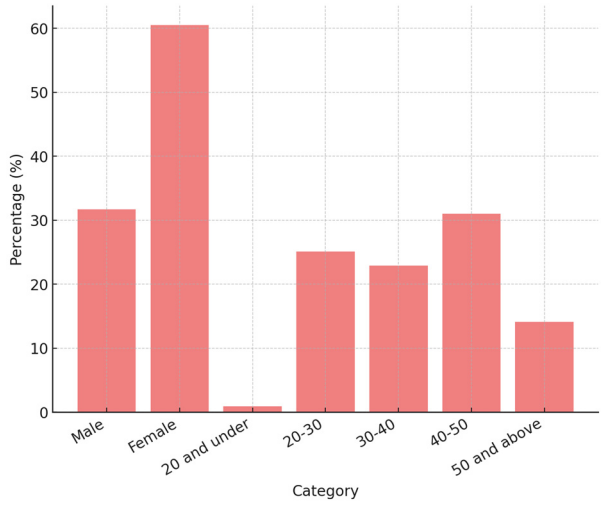


Figure 4. Distribution of participants by gender and age.

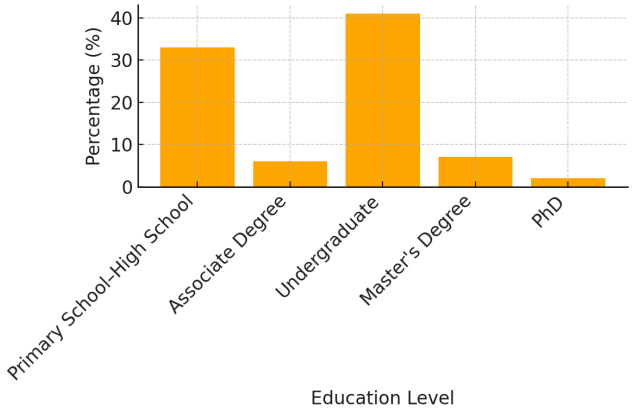


Figure 5. Distribution of participants according to education level, length of employment, and department.

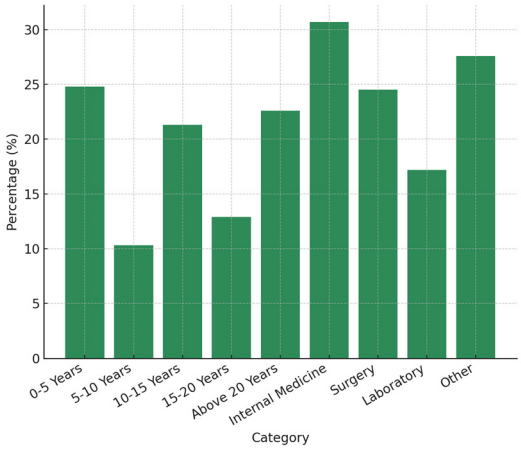


Figure 6. Distribution of participants according to length of employment and department.

3.2.1. Correlation Analysis

In the correlation analyses, the relationships between gender, age, education level, length of employment, and department and the relationships between these variables and factors such as medical waste training and knowledge level, medical waste regulation knowledge level, waste type, pollution knowledge, the perception of the risk of medical waste to human health, and laboratory waste and hazard perception were examined. According to the results, there is a very strong and positive correlation between the length of employment and age ($r = 0.821$, $p < 0.01$), indicating that those who have worked there longer are generally older, which is expected. Knowledge of medical waste regulations tends to decrease as age increases ($r = -0.344$, $p < 0.01$). This may suggest that younger health workers may have more up-to-date knowledge in terms of training and awareness. Those who have worked there longer have less knowledge of medical waste regulations ($r = -0.319$, $p < 0.01$). This suggests that new staff may have received more training on this issue. Notably, younger healthcare professionals and those with fewer years of experience demonstrated higher awareness of waste regulations, suggesting that new employees may receive more frequent training than their senior counterparts [19]. As the education level increases, the level of medical waste training and knowledge increases slightly ($r = 0.104$, $p < 0.05$) [20,21]. However, the correlation is weak, so the education level alone may not be a determinant. It can be seen that female employees are more sensitive than male employees to the impact of medical waste on human health ($r = 0.217$, $p < 0.01$). Those who know about medical waste regulations also have more knowledge of waste types and pollution ($r = 0.231$, $p < 0.01$). In other words, as medical waste knowledge increases, environmental awareness also increases. In addition, those who have received medical waste training are more aware of the dangers of laboratory waste ($r = 0.198$, $p < 0.01$) (Table S1) [11,19,22].

In general, knowledge of medical waste regulations decreases as the length of employment increases, which may indicate the need for training. Younger employees may be more knowledgeable about medical waste regulations. Women are more sensitive to the effects of medical waste on human health. Those who know about waste regulations are more aware of pollution and waste types, and those trained in medical waste have a better understanding of the danger of laboratory waste. These correlations suggest that training programs should focus on specific groups to increase medical waste awareness. In particular, experienced healthcare personnel who have been working for a long time may need to update their knowledge (Figure 7).

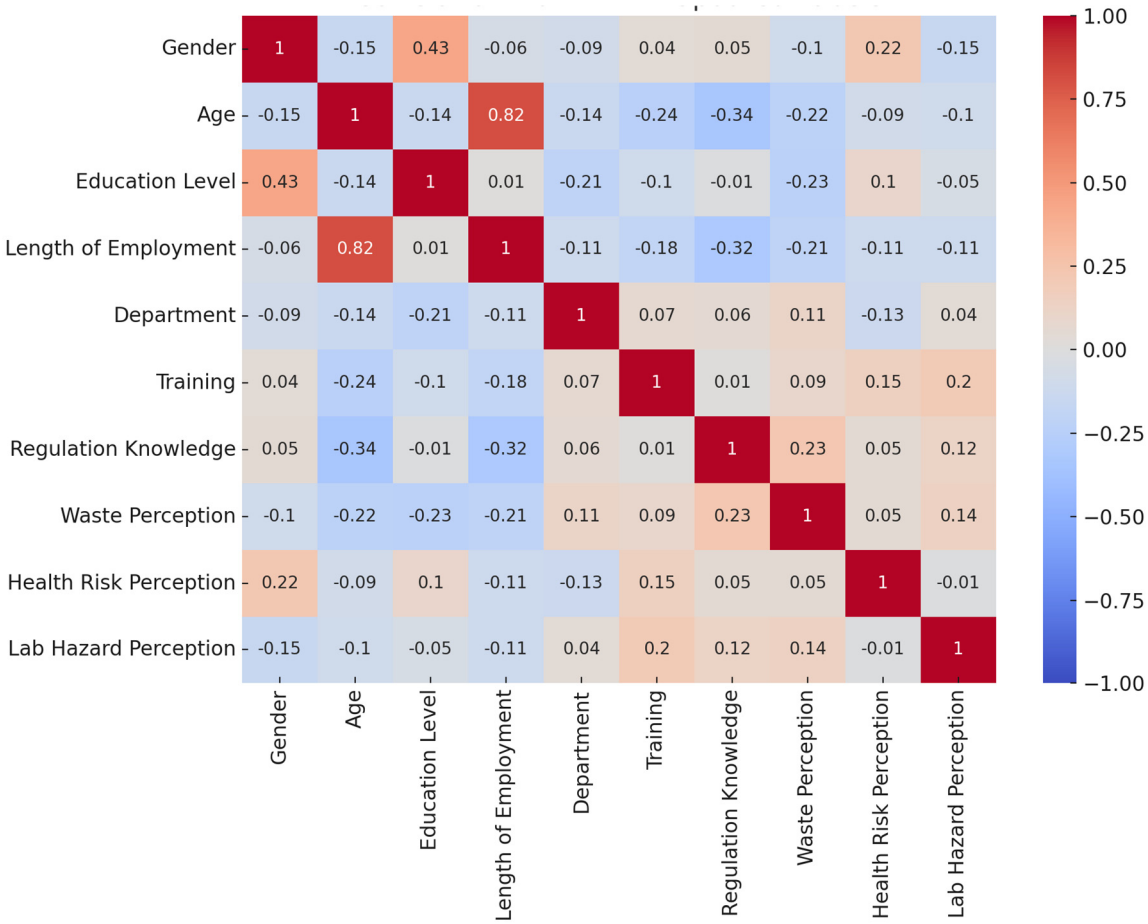


Figure 7. Correlation matrix of variables.

The Chi-square test results revealed that gender ($p = 0.943$) was not significantly related to medical waste training and knowledge level, medical waste regulation knowledge level, waste type and pollution knowledge, the perception of the risk posed by medical waste to human health, or laboratory waste and hazard perception. Similarly, age ($p = 0.782$), length of employment ($p = 0.926$), and department ($p = 0.262$) showed no statistically significant associations with the variables analyzed. All p-values were greater than 0.05, indicating that these demographic variables are independent of the studied outcomes. The lowest p-value was observed for education level ($p = 0.212$), which also did not reach statistical significance. Since some of the data (department variable) have very small expected frequency values (87.5% of the 49 cells have an expected number of less than 5), the reliability of this analysis may be limited in some cases (Table 2).

Table 2. Chi-square t-test results for demographic and employment data.

	Chi-Square Tests									
	Gender		**Age**		**Education Level**		**Length of Employment**		**Department**	
	Value	***p***	**Value**	***p***	**Value**	***p***	**Value**	***p***	**Value**	***p***
Pearson Chi-Square	0.005 [a]	0.943	1.749 [b]	0.782	5.835 [c]	0.212	0.926 [d]	0.921	31.217 [e]	0.262

a. Zero cells (0.0%) have an expected count of less than 5. The minimum expected count is 23.24. b. Two cells (20.0%) have an expected count of less than 5. The minimum expected count is 0.75. c. Two cells (20.0%) have an expected count of less than 5. The minimum expected count is 1.49. d. Zero cells (0.0%) have an expected count of less than 5. The minimum expected count is 8.28. e. Forty-nine cells (87.5%) have an expected count of less than 5. The minimum expected count is 0.26.

3.2.2. Medical Waste Education and Knowledge Level Analyses

In this analysis, the knowledge levels of the participants who received medical waste training on the classification and disposal of medical waste were examined. A total of 301 participants had received medical waste training, and 261 of them considered this training sufficient. A total of 289 received hazardous waste training, and 288 received laboratory waste training.

Of those who received training, 99.2% gave the correct answer for the color of medical waste bags (red). All (100%) of those who did not receive training gave the correct answer. Two people who received training gave the wrong answer. Of those who received medical waste training, 94.2% correctly answered that sharps should be collected in yellow plastic boxes. Among those who did not receive training, 87.8% gave the correct answer. Even among individuals who received training, there were some who answered incorrectly. The Pearson Chi-square test indicates that the relationship between medical waste training and answering the sharps waste question correctly is statistically significant since $p < 0.05$. Therefore, receiving medical waste training seems to positively affect whether the employee knows where to collect sharps waste [23–25]. Although $p = 0.025$ in the Pearson Chi-square test, Fisher's Exact Test was also performed since the expected value in three cells was less than 5, and the results show that $p = 0.048$. In other words, a statistically significant relationship was confirmed. Both Pearson Chi-square ($p = 0.016$) and Fisher's Exact Test ($p = 0.013$) revealed a significant relationship between receiving medical waste training and collecting pathological waste in the right place [26,27]. This indicates that medical waste training is effective, and people who receive training are more likely to implement waste management correctly. There is no significant relationship between receiving medical waste training and knowing the duration of temporary storage of medical waste ($p = 0.625$). Therefore, knowledge of the temporary storage period does not differ between individuals with and without training. Of the 244 people who received medical waste training, 124 gave the correct answer of 48 h. Among those who did not receive training, 15 gave the correct answer. According to the Chi-square test, knowing who is responsible for medical waste in the hospital is not significantly related to participation in medical waste training ($p = 0.566$). Therefore, there is no statistically significant relationship between these two parameters (Table 3).

Table 3. Percentage of those trained in medical waste who gave correct answers on disposal of medical waste.

	Percentage of Correct Answers of Those Trained in Medical Waste		
	%	**Asymptotic Significance (2-Sided)**	**Chi-Square Value**
Color of medical waste bags	99.2	0.853	0.317
Color of sharps waste bags	94.2	0.025	7.351
Collection of pathological waste	88.8	0.016	10.315
Duration of medical waste storage	50.8	0.625	1.753
Knowing person responsible for medical waste	50.9	0.566	3.883

3.2.3. Analyses of Waste Type and Pollution Knowledge

The analyses of waste type and pollution knowledge were based on the classification of expired medicines, the classification of fluorescent lamps, the classification of printer and cartridge waste, the classification of PPE waste, the classification of batteries and accumulators, the classification of genotoxic–cytotoxic pharmaceutical waste, and the collection of liquid hazardous waste. Of the 304 participants, 291, 295, 284, 290, 290, 285, and 291 answered the questions on the classification of expired medicines, fluorescent

lamps, printer and cartridge waste, PPE waste, batteries and accumulators, genotoxic–cytotoxic pharmaceutical waste, and liquid hazardous waste, respectively.

- Significance Level of Knowledge of Waste Types and Pollution by Gender

The accuracy of the answers given for expired medicines, waste toner and cartridges, and waste batteries and accumulators are not significantly related to gender. There is a significant relationship between gender and the classification of waste fluorescent lamps, PPE waste, cytotoxic–genotoxic vial waste, and liquid and hazardous waste. That is, the inclusion of these wastes in particular categories is not due to chance and shows a clear trend (Table 4). These results may indicate that some waste types need to be more clearly defined in regulations or that classification should be based on more precise criteria.

Table 4. Significance levels of waste classification by gender.

Waste Type	%	Asymptotic Significance (2-Sided)	Chi-Square Value	Significance
		Classification of expired medicines		
Medical waste	46.1	0.593	1.902	–
		Classification of waste fluorescent lamps		
Hazardous waste	65.7	0.001	18.076	+
		Classification of waste toner and cartridges		
Hazardous waste	46.1	0.277	3.862	–
		Classification of PPE waste		
Medical waste	44.8	0.004	13.219	+
		Classification of waste cytotoxic–genotoxic drug vials		
Hazardous waste	69.9	0.048	7.915	+
		Classification of waste batteries and accumulators		
Hazardous waste	59.4	0.082	6.706	–
		Classification of liquid and hazardous wastes		
Sealed, leak-proof containers	87.9	0.004	13.219	+

- Significance Level of Knowledge of Waste Types and Pollution by Age

The classification of expired medicines, waste fluorescent lamps, waste toner and cartridges, and waste batteries and accumulators is significantly related to age. There is no significant relationship between age and the classification of PPE waste, cytotoxic–genotoxic vial waste, or liquid and hazardous waste. In conclusion, for some waste types, the classification is quite clear, but for others, different assessments may need to be made. Awareness may need to be raised, especially for cytotoxic–genotoxic vial waste and PPE waste (Table 5).

Table 5. Significance levels of waste classification by age.

Waste Type	%	Asymptotic Significance (2-Sided)	Chi-Square Value	Significance
		Classification of expired medicines		
Medical waste	48.9	0.003	30,045	+
		Classification of waste fluorescent lamps		
Hazardous waste	69.5	0.000	46,891	+
		Classification of waste toner and cartridges		
Hazardous waste	49.2	0.001	33.668	+
		Classification of PPE waste		
Medical waste	44.2	0.181	16.231	–

Table 5. *Cont.*

Waste Type	%	Asymptotic Significance (2-Sided)	Chi-Square Value	Significance
		Classification of waste cytotoxic–genotoxic drug vials		
Hazardous waste	70.9	0.673	9.351	–
		Classification of waste batteries and accumulators		
Hazardous waste	59.9	0.023	23.661	+
		Collection containers for liquid and hazardous waste		
Sealed, leak-proof containers	88.2	0.255	10.150	–

- Significance Level of Knowledge of Waste Types and Pollution According to Education Level

The level of education is significantly related to the correct categorization of waste fluorescent lamps, PPE waste, and cytotoxic–genotoxic drug vial waste. In other words, the inclusion of these wastes in particular categories is not randomly distributed. Education level is not significantly related to the classification of expired medicines, waste toners and cartridges, and waste batteries and accumulators, nor is it related to knowledge of the collection containers of liquid and hazardous wastes. More awareness and education may be needed, especially on the storage methods of expired medicines, toner cartridges, batteries, and liquid wastes (Table 6).

Table 6. Significance levels of waste classification according to education level.

Waste Type	%	Asymptotic Significance (2-Sided)	Chi-Square Value	Significance
		Classification of expired medicines		
Medical waste	45.8	0.094	18.782	-
		Classification of waste fluorescent lamps		
Hazardous waste	66.3	0.008	32.661	+
		Classification of waste toner and cartridges		
Hazardous waste	49.8	0.387	12.757	–
		Classification of PPE waste		
Medical waste	43.9	0.000	53.493	+
		Classification of waste cytotoxic–genotoxic drug vials		
Hazardous waste	70.7	0.002	30.932	+
		Classification of waste batteries and accumulators		
Hazardous waste	60.2	0.299	14.024	–
		Collection containers for liquid and hazardous waste		
Sealed, leak-proof containers	88.2	0.438	7.949	–

- Significance Level of Knowledge of Waste Types and Pollution According to Duration of Employment

Table 7 indicates whether the relationship between the classification of different waste types and the length of employment is statistically significant. There is a significant relationship between the length of employment and the classification of expired medicines, waste fluorescent lamps, waste batteries and accumulators, and liquid and hazardous waste collection containers. There is no significant relationship between the classification of waste toner and cartridges, PPE waste, or cytotoxic–genotoxic drug vial waste and the length of employment. These results show that, for some waste types, the level of experience has an impact on waste awareness, but for other waste types, employees tend to have a similar classification accuracy in general. Training may need to be updated depending on experience, especially for waste types such as fluorescent lamps, expired medicines, and battery/accumulator waste.

Table 7. Significance levels of waste classification according to length of employment.

Waste Type	%	Asymptotic Significance (2-Sided)	Chi-Square Value	Significance
		Classification of expired medicines		
Medical waste	44.7	0.0011	25.901	+
		Classification of waste fluorescent lamps		
Hazardous waste	66.2	0.001	41.037	+
		Classification of waste toner and cartridges		
Hazardous waste	49.6	0.078	19.444	–
		Classification of PPE waste		
Medical waste	44.0	0.757	8.348	–
		Classification of waste cytotoxic–genotoxic drug vials		
Hazardous waste	71.6	0.585	10.352	–
		Classification of waste batteries and accumulators		
Hazardous waste	59.8	0.05	21.025	+
		Collection containers for liquid and hazardous waste		
Sealed, leak-proof containers	88.3	0.026	17.468	+

- Significance Level of Knowledge of Waste Types and Pollution by Department

Table 8 indicates whether the relationship between the classification of various waste types and the department is statistically significant. The evaluation was based on the Chi-square value and *p*-value (Asymptotic Significance, two-sided). The department of employment is significantly related to the classification of waste fluorescent lamps, waste cytotoxic–genotoxic medicine bottles, and the collection containers of liquid and hazardous wastes. There is no significant relationship between the classification of expired medicines, waste toner and cartridges, PPE waste, or waste batteries and accumulators and the department of employment. These results indicate that there is a strong awareness among employees regarding the management of fluorescent lamps, cytotoxic–genotoxic drug vials, and liquid hazardous waste, but awareness may be insufficient or variable for some other waste types [28–30]. In particular, the results suggest that more training or clearer definitions may be needed for expired medicines, toner cartridges, batteries, and PPE waste.

Table 8. Significance levels of waste classification according to the department.

Waste Type	%	Asymptotic Significance (2-Sided)	Chi-Square Value	Significance
		Classification of expired medicines		
Medical waste	47.2	0.096	101.354	–
		Classification of waste fluorescent lamps		
Hazardous waste	66.1	0.000	237.028	+
		Classification of waste toner and cartridges		
Hazardous waste	49.0	0.641	72.929	–
		Classification of PPE waste		
Medical waste	43.9	0.601	77.147	–
		Classification of waste cytotoxic–genotoxic drug vials		
Hazardous waste	71.7	0.050	102.990	+
		Classification of waste batteries and accumulators		
Hazardous waste	59.3	0.656	75.340	–
		Collection containers for liquid and hazardous waste		
Sealed, leak-proof containers	88.4	0.000	111.040	+

- Impact of medical waste on human health and risk perception

According to the answers given by the participants on whether they were affected by medical waste, 61.3% of them thought that they were protected, while 38.7% thought that

they were not. According to the answers given to the question on exposure to health risks posed by medical waste, 33.4% of the participants stated that they were never exposed, while 66.6% stated that they were exposed at different frequencies. The highest exposure frequency was reported to be 29% per week. When asked whether medical waste practices were effective in eliminating risks, more than half of the participants (55.9%) stated that they found them sufficient, while a significant 44.1% stated that they did not find them sufficient. This shows that there are different perceptions about medical waste management (Table 9).

Table 9. Proportion of respondents' answers about their protection from medical waste, exposure to medical waste, and adequacy of medical waste practices with medical waste training.

(%)	Protection from Medical Waste		Exposure to Medical Waste		Finding Medical Waste Practices Adequate	
	Yes	No	Yes	No	Yes	No
Impact of medical waste	61.3	38.7	66.4	33.4	55.9	44.1

Among those who received medical waste training, 64% thought that they were protected from the risks of medical waste. Among those who did not receive training, 42.9% felt protected (Table 10). The proportion of those who felt unprotected was higher among those who did not receive medical waste training (57.1%) compared to those who received training (36%). Table 9 indicates whether feeling protected from medical waste, feeling exposed to medical waste, and finding the practices adequate are statistically significantly related to whether medical waste training was received. Feeling protected from medical waste (%) and finding medical waste practices adequate (%) are significantly related to receiving medical waste training. However, receiving medical waste training does not have a significant effect on the rate of exposure to medical waste [5,6].

Table 10. Respondents' perception of their protection from medical waste depending on whether or not they received medical waste training.

	Rate of Protection from Medical Waste (%)	
	Yes	**No**
Those who received medical waste training	64	36
Those who did not receive medical waste training	42.9	57.1

In general, receiving medical waste training is associated with increased awareness and effectiveness of protection from medical waste and an increased perception that medical waste management practices are adequate. However, receiving training does not directly reduce exposure to medical waste (Table 11).

Table 12 shows the relationships between gender, age, education level, length of employment, and department and the perception of being protected from the effects of medical waste on human health, frequency of exposure to medical waste risks, and the perception of the adequacy of medical waste practices. According to Table 12, gender is most strongly related to education level, but it has no direct effect on the perception of exposure to and protection from medical waste ($p > 0.05$). There is a strong relationship between age and length of employment, but age has no significant effect on the perception of protection from medical waste or the adequacy of practices. This suggests that younger and older employees have similar perceptions of medical waste. More educated employees may be more critical of medical waste management practices. However, there is no significant relationship between the perception of protection and education level ($p > 0.05$). The length

of employment and age are directly related to each other, but the length of employment has no significant effect on the perception of protection from medical waste or the perception of the adequacy of management practices ($p > 0.05$). This may indicate that employees need to update their knowledge about medical waste, even if they have many years of experience. The education level of employees in some departments may be lower, but the department has no significant effect on the perception of medical waste management ($p > 0.05$). It can be said that employees working in different departments have similar levels of awareness about medical waste management.

Table 11. The significance of the relationship between receiving medical waste training and feeling protected from medical waste, feeling exposed to medical waste, and finding medical waste practices adequate.

(%)	Protection from Medical Waste		Exposure to Medical Waste		Finding Medical Waste Practices Adequate	
	Asymptotic Significance (2-Sided)	Chi-Square Value	Asymptotic Significance (2-Sided)	Chi-Square Value	Asymptotic Significance (2-Sided)	Chi-Square Value
Those who received medical waste training	0.016	5.761	0.089	6.516	0.006	7.352
Significance	+		−		+	

Table 12. The relationships of gender, age, education level, length of employment, and department variables with the frequency of exposure to medical waste, the perception of protection from medical waste, and the perception of the adequacy of medical waste practices.

Control Variables			Gender	Age	Education Level	Length of Employment	Department
Perception of protection from effects of medical waste on human health, Frequency of exposure to medical waste risks, and Perception of adequacy of medical waste practices	Gender	Correlation	1.000	−0.099	0.383	−0.023	−0.027
		Significance (2-Tailed)	.	0.115	0.000	0.719	0.664
		df	0	252	252	252	252
	Age	Correlation	−0.099	1.000	−0.082	0.827	−0.154
		Significance (2-Tailed)	0.115	.	0.191	0.000	0.014
		df	252	0	252	252	252
	Education level	Correlation	0.383	−0.082	1.000	0.049	−0.187
		Significance (2-Tailed)	0.000	0.191	.	0.434	0.003
		df	252	252	0	252	252
	Length of employment	Correlation	−0.023	0.827	0.049	1.000	−0.126
		Significance (2-Tailed)	0.719	0.000	0.434	.	0.044
		df	252	252	252	252	252
	Department	Correlation	−0.027	−0.154	−0.187		1.000
		Significance (2-Tailed)	0.664	0.014	0.003		.
		df	252	252	252		0

3.3. Evaluation of Hypotheses

3.3.1. Evaluation of Main Hypotheses

H1: *A higher education level and frequency of training significantly increase healthcare workers' knowledge of and compliance with medical waste management protocols.*

This hypothesis was supported. The regression analysis ($R^2 = 0.72$, $p < 0.01$) showed that the frequency of training was the strongest predictor of compliance. In addition, healthcare workers who received training had greater waste management knowledge.

H2: *The duration of employment alone does not improve medical waste classification accuracy.*

This hypothesis was supported. Correlation analyses showed that there was no significant relationship between the length of employment and waste management knowledge ($r = -0.319$, $p < 0.01$). The knowledge of those who have worked longer is more outdated, and younger health workers who have received training are more accurate classifiers.

H3: *Waste management in the microbiology laboratory is subject to more misclassification than general hospital waste management.*

This hypothesis was supported. The results of this study show that 15% of hazardous wastes were misclassified. In particular, fluorescent lamps, cytotoxic drug bottles, and expired drugs were placed in the wrong categories.

H4: *The rate of misclassification of waste types can be reduced through special training programs.*

This hypothesis was partially supported. Although trained employees had lower misclassification rates, some categories (e.g., cytotoxic drugs and fluorescent lamps) still had a high error rate. This indicates the need for more specific and repeated training.

H5: *The misclassification of hazardous waste increases occupational risks to healthcare workers.*

This hypothesis was supported. A total of 66.6% of workers reported exposure to medical waste due to waste mismanagement. In addition, 44.1% of the respondents stated that medical waste management practices were inadequate.

3.3.2. Evaluation of Sub-Hypotheses

H6: *Young healthcare workers have more up-to-date knowledge about medical waste management regulations.*

The hypothesis was supported. Correlation analysis revealed a negative relationship between age and knowledge of medical waste regulations ($r = -0.344$, $p < 0.01$). Younger healthcare workers' knowledge was more up-to-date and accurate.

H7: *Healthcare workers with higher education levels make more accurate decisions about waste classification.*

The hypothesis was partially supported. The higher the level of education, the higher the level of knowledge ($r = 0.104$, $p < 0.05$), but this alone did not significantly increase the accuracy of waste classification.

H8: *The amount of waste generated in the bacteriology unit is significantly higher than in other laboratory units.*

The hypothesis was supported. The bacteriology unit generated an average of 5.94 kg of medical waste per day, while other units (parasitology, microbiology, etc.) generated lower levels of waste.

H9: *The misclassification of medical waste leads to increased environmental pollution and public health risks.*

This hypothesis was supported. The results indicate that misclassified hazardous wastes can be harmful to the environment and create risks by leaking outside the hospital.

H10: *Mandatory and regular training programs are an important factor in increasing compliance with medical waste management protocols.*

The hypothesis was supported. Healthcare workers who received training were found to be more conscious of and compliant with medical waste management. However, it was emphasized that training should be repeated at regular intervals.

Of the ten hypotheses tested in this study, eight were fully supported, and two were partially supported. These findings emphasize the need for increased training programs, raised awareness of certain waste categories, and regular inspections.

Although healthcare professionals demonstrated high levels of knowledge in the questionnaire, observational data from the microbiology laboratory revealed that this knowledge was not always translated into correct waste handling practices. For example, expired drugs and cytotoxic vials were misclassified during on-site monitoring, despite high scores on related questionnaire items.

This discrepancy highlights the importance of using both self-reported and observational data when assessing waste management performance. Accordingly, self-reported compliance may overestimate actual behavior, and that combining different data collection methods allows for a more accurate evaluation and targeted improvements.

While this study adhered to the Turkish Regulation on the Control of Medical Wastes [16], which constitutes the national legal framework for waste classification and disposal in healthcare settings, it is important to acknowledge the broader international context provided by the World Health Organization (WHO). The WHO's classification system groups healthcare waste into eight categories—infectious, pathological, sharps, chemical, pharmaceutical, genotoxic, radioactive, and general non-hazardous—offering a more universally standardized structure. Some differences between the two systems exist; for instance, certain types of PPE and cytotoxic waste are more explicitly defined in the WHO model. Although the present study's findings are aligned with the national regulation, future research may benefit from incorporating WHO's categorization in parallel to enable international benchmarking and facilitate cross-border comparisons. This dual-framework approach could improve the global applicability of research outcomes without undermining local regulatory compliance.

4. Conclusions

This study highlights significant challenges in medical waste management within microbiology laboratories, particularly concerning the misclassification of hazardous wastes and inconsistent compliance with disposal protocols. The laboratory generated an average of 22.78 kg/day of medical waste, 11.67 kg/day of liquid hazardous waste, and 5.61 kg/day of sharps waste, with the bacteriology unit identified as the largest contributor.

When normalized by the hospital's capacity of 1306 beds, this corresponds to approximately 17.44 g/bed/day of medical waste, 8.93 g/bed/day of liquid hazardous waste, and 4.29 g/bed/day of sharps waste. These values offer a scalable metric for benchmarking and cross-institutional comparison. Misclassification was notably prevalent for expired pharmaceuticals and cytotoxic–genotoxic pharmaceutical wastes, underscoring specific training and regulatory compliance gaps. Higher training frequency significantly improved classification accuracy, whereas work experience alone was insufficient. Implementing mandatory recurring training, stricter monitoring, clear labeling systems, and digital tracking is recommended; however, practical barriers such as budgetary constraints, infrastructural deficiencies, and potential personnel resistance must be acknowledged. Furthermore, this research was conducted in a single institution, limiting generalizability, and relied partly on self-reported survey responses, indicating potential subjective biases. Future studies should investigate the sustained impact of educational interventions and assess how automation and artificial intelligence can further optimize hospital waste management. These findings provide actionable data that hospitals can utilize to enhance occupational safety, environmental protection, and compliance with both national and international waste management regulations.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su17104325/s1: Table S1: Demographic variables and waste awareness level correlations.

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Abbreviations

The following abbreviations are used in this manuscript:

PPE	Personal protective equipment
ISTAC	Istanbul Environmental Management Industry and Trade Inc.

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