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Research Paper

Sustainable Alternatives for Chemical Waste Management in Testing and Calibration Laboratory

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Abstract
Laboratory waste represents a growing global concern due to its potential impacts on environmental quality, human health, and safety when improperly managed. At IPB University, laboratory activities generate up to 5 tons of wastewater per month, emphasizing the need for effective and sustainable waste management strategies. This study proposes a structured gap-to-roadmap framework for independent chemical waste management in testing and calibration laboratories. The framework integrates criteria-based gap analysis, a literature-derived waste minimization checklist, and phased implementation planning. Data were collected through semi-structured interviews and literature review, and analyzed using a qualitative, criteria-based approach. The results indicate that the PPLH IPB Laboratory generates approximately 100–481 L of chemical waste annually. While several minimization practices have been implemented, key gaps remain in standard operating procedures, labeling systems, temporary storage, and recovery and recycling practices. The checklist analysis further identifies feasible strategies, including solvent recycling and inter-laboratory chemical exchange, with significant potential for waste reduction and improved resource efficiency. The proposed framework translates identified gaps into targeted actions and assigns them into short-, medium, and long-term implementation phases. This approach provides a practical and replicable tool for laboratories seeking to transition toward independent, compliant, and environmentally sustainable waste management systems, particularly in resource-constrained settings.

Keywords
Green, Management, Sustainability, Toxic, Wastewater

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1. INTRODUCTION

Laboratories encompass various types, including educational, research, testing, and calibration laboratories (Pillai et al., 2022). Testing and Calibration Laboratories (LPK) play a critical role in ensuring the safety and quality of various materials and products. In Indonesia, more than 2,000 LPKs were recorded in 2024 (Badan Standardisasi Nasional, 2024). The increasing number of laboratories has raised concerns regarding the generation and management of chemical waste. Although laboratory waste is typically produced in relatively small quantities, it often contains highly toxic and hazardous substances that pose significant risks to environmental and human health (Nwobi et al., 2024). Improper management of laboratory waste can result in the release of hazardous gases, environmental degradation, and safety risks (Aimi and Wahab, 2022; Alam et al., 2021; Nwobi et al., 2024). In particular, chemical waste may contain heavy metals that can disrupt ecosystems and contribute to adverse health outcomes in surrounding communities (Nwobi et al., 2024). Therefore, effective laboratory waste management is a key component of sustainable laboratory practices (Hakim et al., 2023; Nwobi et al., 2024).

The Environmental Research Center Laboratory (PPLH IPB Lab), as one of the testing laboratories, conducts extensive environmental testing activities, including water, air, and soil quality analysis. In 2024, the laboratory carried out up to 32 testing activities, each involving 13–23 types of analyses, resulting in approximately 481 L of chemical waste. Currently, waste is managed through segregation based on KAN-G-15 categories. KAN-G-15 provides technical guidelines for laboratory waste management in Indonesia (National Accreditation Body of Indonesia, 2016). However, environmental laboratory regulations changed in 2020, but there have been no updates to the technical guidelines. Subsequently, the segregated laboratory waste is treated by licensed third-party providers (ex-situ). However, reliance on third-party services presents several challenges, such as requires transport vehicles that meet the criteria, limitations in services and controls, costs and a lack of qualified officers (Rugeiyamu, 2025). Based on this, it is necessary to carry out laboratory waste management independently (in situ) by applying the hierarchical principles of waste management from minimization, reuse, recycle, treatment, and safe disposal (Pribadi et al., 2020).

Independent management of laboratory waste by applying the principle of the waste management hierarchy is often not carried out optimally. Lack of understanding of waste management, limited facilities, and resources are challenges in implementing these principles (Akhdiyat et al., 2025). This study represents an initial step toward planning the management of laboratory chemical waste independently for small-to-medium scale laboratory.

Previous studies in Indonesia and the ASEAN regios have primarily focused on evaluating compliance, identifying waste characteristics, or assessing environmental risks, with limited emphasis on translating findings into structured and implementable management strategies (Siril et al., 2022; Utami et al., 2024; Wirodimurtia et al., 2022). Gap analysis has been widely used to identify discrepancies between current practices and desired standards and to inform corrective actions. However, existing approaches often stop at problem identification or general action planning, with limited integration into structured implementation pathways. Therefore, this study aims to develop a structured implementation framework for independent laboratory chemical waste management in testing and calibration laboratories by integrating criteria-based gap analysis, targeted action formulation, and phased implementation planning. By explicitly linking gap identification with actionable strategies and temporal prioritization, this study contributes a practical and replicable approach that bridges the gap between assessment and implementation in laboratory waste management.

2. EXPRIMENTAL SECTION

2.1 Materials

This research was carried out at the Laboratory of the Environmental Research Center, Bogor Agricultural University (PPLH IPB Lab) in Bogor Regency, West Java Province, Indonesia. The research was conducted from April to June 2025. Data collection was supported by field documentation and qualitative assessment tools, including a questionnaire, digital camera, and audio recorder for documentation and interviews.

2.2 Methods

Understanding the existing waste management system is essential for identifying appropriate corrective actions. Therefore, chemical waste management practices at the PPLH IPB Laboratory were evaluated using a qualitative gap analysis approach (Pillai et al., 2022). The gap analysis was conducted using a criteria-based evaluation framework derived from national regulatory standards (e.g., Ministry of Environment and Forestry Regulation No. 6/2021) and literature that established best practices in laboratory waste management.

Each criterion was systematically assessed by comparing current laboratory practices with the defined standards and literature to identify discrepancies. Based on the identified gaps, targeted recommendations were directly formulated to improve compliance, operational efficiency, and environmental performance (Pillai et al., 2022). To support the development of waste minimization strategies, relevant practices were identified through a literature review using the Scopus database. The search employed keywords such as "waste minimization practice," "green laboratory," and "sustainable research laboratory." Inclusion criteria consisted of peer-reviewed journal articles and systematic reviews focusing on chemical waste management in laboratory settings, while studies addressing non-laboratory waste sources were excluded. In addition, technical guidelines for environmental laboratory waste management (KAN-G-15) were used as a complementary reference (National Accreditation Body of Indonesia, 2016). The identified practices were compiled into a waste minimization checklist to facilitate comparison with existing laboratory practices.

Furthermore, semi-structured interviews were conducted with the Head of Laboratory and personnel of the PPLH IPB Laboratory in May 2025 to validate current practices and assess the feasibility of implementing identified recommendations. The interviews were conducted on-site at the laboratory. The collected qualitative data were analyzed through thematic interpretation and subsequently verified by the interviewees to ensure accuracy and credibility (Goh et al., 2019). Finally, the findings from the gap analysis, literature review, and stakeholder input were integrated to develop a structured implementation framework. This framework consists of three sequential components: (1) criteria-based gap identification, (2) reccommendation actions, and (3) allocation of actions into short-, medium-, and long-term implementation phases based on feasibility considerations, including technical requirements, infrastructure readiness, and regulatory constraints (Anaç et al., 2024). This approach enables a systematic linkage between identified gaps and an actionable implementation roadmap.

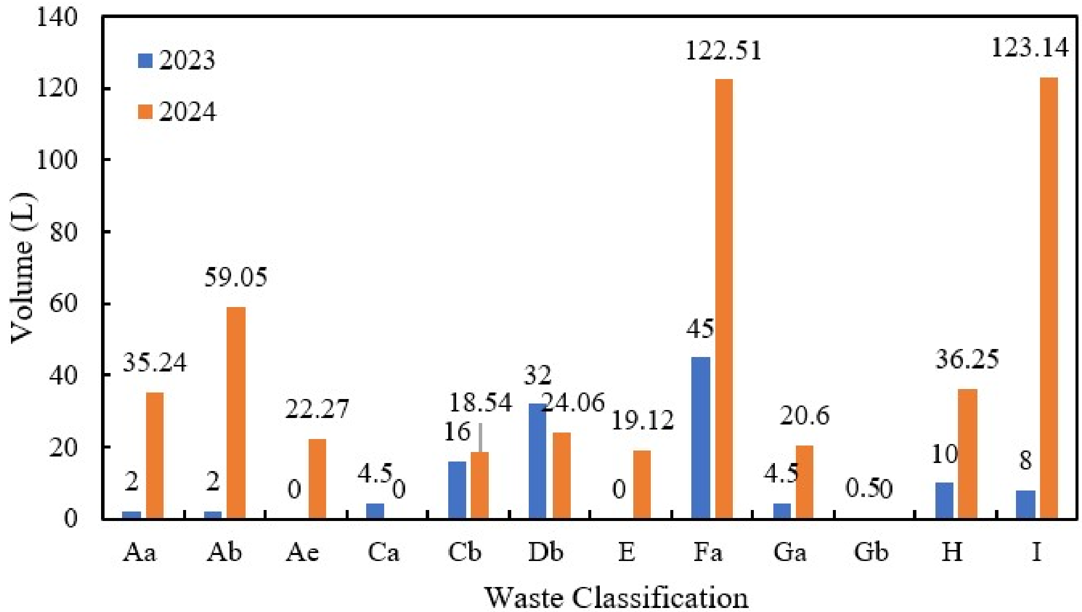

Figure 1. Waste Balance of IPB PPLH Lab in 2023 and 2024. Category: Aa. Organic and Flammable Solvents; Ab. Organic Solvents Containing Halogens; Ae. Non-Flammable Organic Solvents; Ca. Fluoride or Inorganic Phosphorus; Cb. Fluoride or Phosphorus Containing Organic Materials or Heavy Metals; Db. Mercury Compounds; E. Chromic Acid; Fa. Inorganic Heavy Metals; Ga. Strong Acid (Does Not Contain Others); Gb. Strong Base (Does Not Contain Others); H. Silver Metal; I. Others

Table 1. Analytical Methods and Associated Waste Profiles

Testing	Methods	Waste Category	Key Hazardous Component
Chemical Oxygen Demand (COD)	Spectrophotometry	Db	Mercury (Hg)
Nitrogen Total	Spectrophotometry	Fa	N-(1-naphtyl)-ethylenediamine dihydrochloride (NED), dissolved Cd and Cu
Ammonia (NH_3-N)	Spectrophotometry	Aa	Phenol, sodium nitroprusside
Nitrite (NO_2-N)	Spectrophotometry	I	Sulfanilamide ($H_2NC_6H_4SO_2NH_2$), NED dihydrochloride, potassium permanganate ($KMnO_4$)
Nitrate (NO_3-N)	UV-vis Spectrophotometry (cadmium reduction)	Fa	Sulfanilamide, NED dihydrochloride, dissolved Cd and Cu
Chloride (Cl^-)	Titrimetric	H, I	Silver (Ag), Chromium (Cr)
Total Phosphorus (Total P)	Spectrophotometry	Cb	Molybdenum
Hexavalent Chromium (Cr-VI)	Spectrophotometry	E	Cr (VI)
Dissolved metal	Spectrophotometry	Fa	Copper (Cu), Zinc (Zn), Cobalt (Co), Nickel (Ni), Cadmium (Cd), Lead (Pb)
Total Hardness (Ca and Mg)	Spectrophotometry	I	Na_2EDTA, Ca-EDTA, Eriochrome Black T (EBT)
Permanganate	Titrimetric	Fa	Manganese (Mn), sodium oxalate

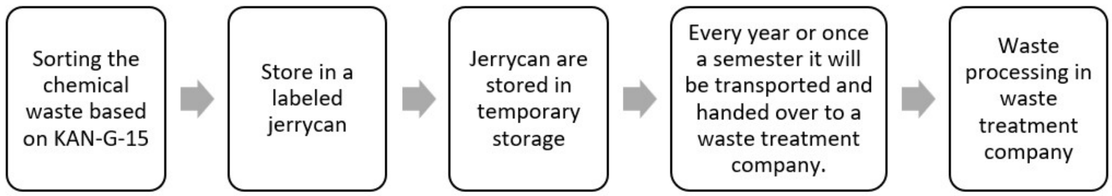

Figure 2. Waste Management Procedures for PPLH IPB Lab

Table 2. Waste Minimization Practices That Have Been Carried Out by the PPLH IPB Lab

Waste Minimization Practices	Reference
There are staff members responsible for inventory control;	(Goh et al., 2019)
Chemical purchases are recorded to guarantee that the chemicals have been used up before purchasing new ones;	(Goh et al., 2019)
Purchases that are not excessive so that they do not store expired materials;	(Goh et al., 2019)
Proper storage according to its characteristics;	(National Accreditation Body of Indonesia, 2016)
Periodic checks in the storage room for damage or spillage of chemicals;	(Bayrau et al., 2025)
Chemical extraction from the storage room with a FIFO (first in first out) system;	Goh et al. (2019)
Manufacture of reagents according to their needs and labeling.	(National Accreditation Body of Indonesia, 2016)

3. RESULTS AND DISCUSSION

3.1 Evaluation of Laboratory Waste Management

3.1.1 Laboratory Waste Management Procedure Policy

Government Regulation No. 22 of 2021 concerning the Implementation and Protection of the Environment Article 274 states that "everyone who produces waste is obliged to manage the waste they produces". Based on the Regulation of the Ministry of Environment and Forestry Regulation No. 6 of 2021 concerning Procedures and Requirements for B3 Waste Management, Article 105 and Article 123 state that waste producers are obliged to carry out waste utilization and treatment, but if they are unable to do it themselves, they can be handed over to the B3 waste utilizer and/or processor If the B3 waste producer utilizes and processes waste directly, it is necessary to apply for technical approval for B3 waste management to the Ministry of Environment. However, based on the same regulation, Article 121 paragraph (1) states that "B3 waste producers who utilize waste through the reuse of waste generated from their own activities in a closed production process system, reuse of B3 waste packaging to package B3 waste with the same characteristics, reuse of B3 waste in limited and non-continuous quantities, and laboratory-scale research, exempt from the obligation to have technical approvals". Although the planned management is exempt from applying for technical approval, this needs to be reconfirmed to the Ministry of Environment. The regulation in Article 121, paragraph (2), laboratories as waste producers need to document and report on their management processes to the Environment Agency. In addition, if the laboratory is certified as an environmental laboratory, one of the requirements is a temporary waste storage permit and a waste management technical approval. Therefore, laboratories are still advised to apply for technical approval for B3 waste management.

Based on the Ministry of Environment and Forestry Regulation No. 23 of 2020 concerning Environmental Laboratories, laboratories need to develop policies related to laboratory waste management. There is no internal policy related to waste management at the PPLH IPB Lab. Based on this, the PPLH IPB Lab must develop a waste management policy that every laboratory user must obey. The drafted regulations must be flexible enough to accommodate practices and innovations in the laboratory without sacrificing safety or environmental protection. Regulations and their implications need to be socialized to each laboratory personnel so that waste management can be appropriately implemented and avoid accidental errors that are dangerous to safety. The policy implementation needs to be evaluated periodically to ensure the effectiveness and efficiency of chemical waste management in the laboratory.

3.1.2 Laboratory Waste Balance

Waste balance is compiled to determine the quantity of chemicals that become waste. Waste balance is important to reduce chemical waste and ensure the efficiency of chemical use. The waste balance document prepared consists of the

Figure 3. Utilization of Testing Waste with Hydroponics

Table 3. Evaluation Results and Recommended Action for Improving Laboratory Waste Management Practice at PPLH IPB Lab

Criteria	Evaluation Results	Recommended Actions
Policy	Key practices implemented: segregation, labeling, FIFO inventory	Develop internal policies and SOPs, Reduce storage duration
Waste Minimization	Practices include controlled procurement, proper storage, labeling, and need-based reagent preparation	Improve chemical efficiency, Chemical exchange program, treatment via precipitation/ oxidation/reduction
Waste Management	Handled by certified third-party hazardous waste service providers	Initiate in situ management: recycling, recovery, reuse, hazard reduction
Waste Storage	No temporary storage permits available	Reduce storage reduction
Monitoring and Reporting	Annual recording and reporting conducted	Submit report to authorities
Mass Balance	Waste increased to 480.78L in 2024; dominated by inorganic heavy metals	Apply recovery and recycling strategies

type and volume of laboratory wastewater that is managed by itself and transported to a third party. In 2023 and 2024, all waste will be transported to third parties. There will be an increase in the volume of waste up to almost 4 times in 2024, from 124.50 liters/year to as much as 480.78 liters/year. The increasing number of testing activities causes an increase in waste volume carried out at the PPLH IPB Lab in 2024. Since that year, the PPLH IPB Lab has received accreditation as an Environmental Laboratory. The cost incurred for transportation and processing is Rp. 6,600,000. The volume of PPLH IPB Lab waste is presented in Figure 1.

The waste volume data indicate that inorganic heavy metal waste (122.51 L) and miscellaneous waste (123.14 L) were dominant categories in 2024 (Figure 1). This dominance can be directly linked to analytical methods employed by the PPLH IPB laboratory (Table 1). In 2024, chloride and hardness testing waste will be included in other categories, increasing the volume of waste in this category. Inorganic heavy metal waste is primarily generated from titrimetric and oxidative analytical methods, including dissolved metal analysis and permanganate testing. These methods require large reagent volumes and produce approximately 1.5 L of wastewater per test, leading to cumulative waste generation. Similarly, the miscellaneous waste category increased substantially due to chloride and hardness testing, which produce effluents not classified under specific KAN-G-15 categories. The rise in routine water quality testing following laboratory accreditation in 2024 further amplified the contribution of these methods to overall waste generation. In addition, in 2023, there will be Florida waste and strong alkaline because there are initial experiments to analyze and verify the Florida analysis test method. Then it was not continued in 2024, so these types of waste were not existed in 2024.

3.1.3 Laboratory Waste Management

Waste from the PPLH IPB Lab is sorted and transported to a waste management company. Waste treatment outside the laboratory can be carried out in accordance with the

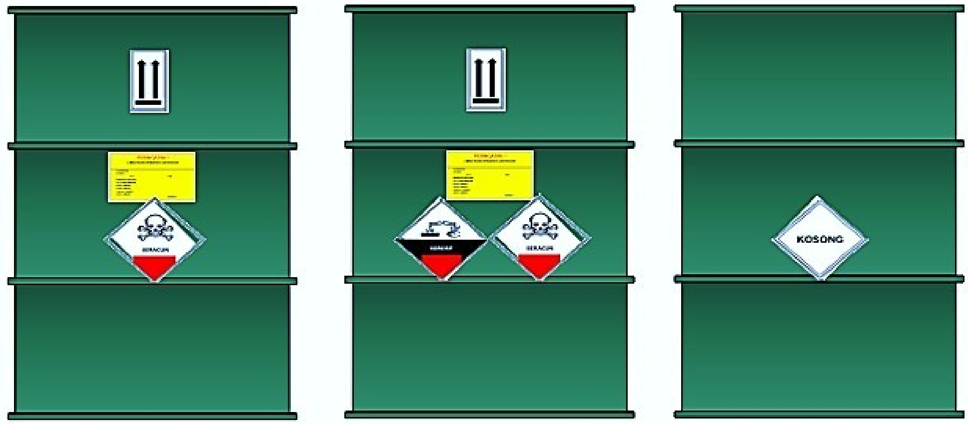

Figure 4. Example of B3 Waste Packaging Labels Based on the Ministry of Environment and Forestry Regulation No. 6 of 2021 Concerning Procedures and Requirements for B3 Waste Management

Table 4. Potential Areas for Improvement of Waste Minimization Practices at the PPLH IPB Lab

Waste Minimization Practices	Reference
Reduction	
Efficient use of chemicals by using them until the final product or until they go into the recycling process	(Kernaghan et al., 2024)
Reuse	
Using recycled chemicals	(Kernaghan et al., 2024)
Excess chemical exchange program with other institutions/laboratories	(Goh et al., 2019)
Recycle	
Acetone waste is collected and recycled using fractional distillation.	(Bayrau et al., 2025)
Turning hazardous chemicals into commercial materials	(Bayrau et al., 2025)
Treatment	
Processing hazardous waste into non-hazardous/less hazardous waste by precipitation, oxidation, and/or reduction	(Goh et al., 2019)

waste management technical guidelines for environmental laboratory accreditation. This is due to the absence of a wastewater management installation (WWTP) in the PPLH IPB Building, which is due to the limited land available. The waste management procedures carried out at the PPLH IPB Lab can be seen in Figure 2.

The waste generated from each test is categorized into categories to minimize the risk of harm to the environment and the safety of waste management officers, prevent cross-contamination, and assist in specific waste management requirements (González et al., 2020; Nwobi et al., 2024). Based on KAN-G-15, there are 8 (eight) categories of chemical waste namely A (Organic Solvents), B (Cyanide), C (Fluoride and Phosphor), D (Mercury), E (Chromatic Acid), F (Heavy Metals), G (Acids and Bases), and H (Others) (National Accreditation Body of Indonesia, 2016).

The sorted waste can then be included in packaging labeled with the waste category and the hazard level. The waste is stored in labeled containers (jerry cans) and then stored in a temporary storage area. A color-coded system can be used to facilitate label identification. Waste sorting is part of the draft SOPs for waste management to ensure that all laboratory personnel can properly sort. Every 6 (six) months or a year, the waste will be transported to the waste treatment site. The PPLH IPB Lab collaborates with an international waste treatment company to manage its chemical waste. The cost is Rp6,600,000 for transportation and processing.

The PPLH IPB Lab is independently developing innovations in chemical waste treatment. The PPLH IPB Lab began to research the use of laboratory liquid waste. B3 waste for laboratory-scale research does not require a B3 waste management permit (Ministry of Environment and Forestry Regulation No. 18 of 2020). Based on this, the PPLH IPB Lab can conduct research on the use of laboratory waste. The research was carried out by utilizing waste from testing for hydroponics, shown in Figure 3. Morphological observations of the experimental plants indicate

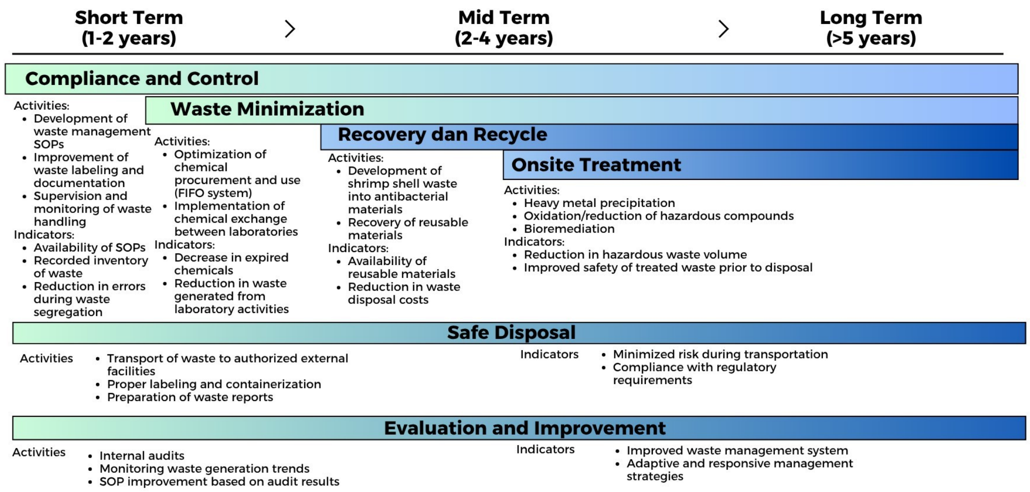

Figure 5. Proposed Laboratory Waste Management Roadmap

that water spinach has the potential to accumulate heavy metals from laboratory wastewater; however, the quantitative differences in metal concentrations before and after treatment have not yet been analyzed. Independent waste management has challenges such as limitations in treatment facilities and the need for additional costs. However, treating waste independently can reduce the environmental burden, reduce the waste produced, and increase knowledge related to laboratory waste management (Nwobi et al., 2024).

3.1.4 Temporary Waste Storage

A temporary waste storage permit is required because laboratory waste contains hazardous and toxic materials (B3). Temporary waste storage permits are required to minimize the negative impact of waste, support safe waste management, and monitor waste that has been stored and transported to third parties. The PPLH IPB lab does not yet have a temporary waste storage permit. The cause is the lack of space and budget for waste storage infrastructure. This condition can increase the potential risk of pollution to the environment and risk to safety in the laboratory. To minimize the potential risk of pollution and danger, waste storage is sorted by type, routine inspections are carried out once a year, and research is started for independent liquid waste treatment so that it can reduce the amount of waste transported.

3.1.5 Waste Minimization Practices

Waste minimization is the main stage in waste management because it can reduce the potential for environmental contamination. Thus, it can protect the ecosystem, reduce hazards to health and safety, and save waste treatment and disposal costs (Barbosa et al., 2020). Waste minimization practices that the PPLH IPB Lab has carried out are presented in Table 2.

Some of the efforts made by the PPLH IPB Lab to minimize the waste produced include storage according to its characteristics in a safe place and at an appropriate temperature (Malaha, 2023). The chemicals are stored in tightly sealed containers with clear labels. Chemical storage must be done appropriately to reduce the risk of safety hazards to laboratories and environmental contamination (Malaha, 2023). Samples are also stored in a suitable place, generally at low temperatures (around 2-8 °C), to prevent biomolecular degradation so that the samples remain viable for long-term analysis (Baust, 2016).

Chemical extraction from the storage room with a first-in-first-out (FIFO) system is carried out to optimize stock management and material use efficiency (Malaha, 2023). Checks on expired, damaged, and exhausted materials are carried out at the end of every month. After checking, a purchase will be made so that the purchase is not excessive (Kuzmina et al., 2022). Suppliers selected by the PPLH IPB Lab do not accept expired materials, as additional fees are required for return accommodation. Therefore, expired materials are managed by laboratories as part of laboratory chemical waste (Nwobi et al., 2024).

3.1.6 Waste Management Monitoring and Reporting Data

Waste management monitoring and reporting data is often overlooked because it is considered non-urgent and important to be done shortly. Nevertheless, recording needs to be done to monitor the amount of waste produced and the effectiveness of waste management (Akhdiyat et al., 2025). According to the Ministry of Environment and Forestry Regulation No. 23 of 2020 concerning Environmental Laboratories, it is stated that laboratories must compile waste monitoring data and report it to authorized officials. PPLH IPB Lab Staff compile monitoring data and waste manage-

Table 5. Recovery Efficiency and Waste Reduction Potential of Chemical Waste Management

Material	Recovery/Recycle/Reuse Strategy	Chemical Waste Reduction Potential	Recovery Efficiency (%)	Reference
Solvent	Acetone recovery and reuse for analytical applications	Reduced solvent waste through distillation and reuse	∼83.7	(Coletti et al., 2019)
	Toluene/Ethyl Acetate recovery and reuse for analytical applications	Reduced solvent waste through modified distillation systems	65-90	(Zweckmair et al., 2017)
Silver	Recovery of silver residue and reuse as silver nitrate	Reduced silver-containing residues and decreases the demand for $AgNO_3$ purchase	∼95%	(Steed and Hayes, 1972)
	Recovery of silver from laboratory waste for Ag/AgCl electrode production	Recovered the silver residue and reuse for working electrode for chloride determination	Unknown. The purity of the extracted silver ranged from 89.4% to 97.0%	(Kanna et al., 2016)
	Conversion of AgCl waste into high-purity microcrystalline silver using H_2O_2	Converts AgCl waste into reusable silver microcrystals, enabling its application in the fabrication of wearable silver jewelry	∼91.27	(Gatemala et al., 2017)
	Recovery of Ag from AgCl and reuse as silver nitrate using modified Thomas and Willbanks methods	Reduces AgCl residues and decreases the demand for $AgNO_3$ procurement	91.3-99.7%	(von Dollen et al., 2018)
	Utilization of argentometric waste for synthesis of silver nanoparticles (AgNPs)	Reduces argentometric waste through its conversion into value-added nanomaterials	Unknown	(Gusrizal et al., 2021)
Copper (Cu)	Recovery of copper as copper sulphate pentahydrate for treating laboratory wastewater	Reduction of organic dye pollutants	96%	(Rai and Paulson, 2025)
	Reuse of Cuprous Oxide as an active catalyst for the synthesis of a variety of 1,4-disubstituted 1,2,3 triazole	Prolongs the operational lifespan of copper materials	97%	(Rai, 2025)

ment reports once a year.

3.1.7 Identified Gaps

Based on the evaluation conducted, key findings and research gaps can be identified based on the parameters set out in Ministry of Environment and Forestry Regulation No. 23 of 2020 concerning Environmental Laboratories (Table 3). Table 3 indicates that the PPLH IPB Laboratory has implemented several waste management practices in accordance with the applicable regulations. On the other hand, several analytical gaps and recommendations remain that can be addressed by the PPLH IPB Laboratory to improve and implement independent and sustainable laboratory waste management.

3.2 Recommended Action for Laboratory Chemical Waste Management

3.2.1 Potential Areas for Improvement

Laboratory Chemical waste management can be carried out independently by the PPLH IPB Lab by applying the principles of waste management hierarchy, such as prevention, reduction, reuse, recycling, processing, and safe disposal. The most recommended option is the prevention of waste generation. Prevention can be done at the planning stage by reducing the use of materials and planning for the extension of the life of the material. Minimization can be done when it is impossible to prevent waste generation (Banford, 2023). Minimize waste by planning testing activities using single-use materials and replacing them with non-hazardous or less hazardous chemicals (Banford, 2023; Pribadi et al., 2020). When waste is still generated, further efforts must be made by reuse or recycling (Banford, 2023). Before reuse and recycling, waste separation needs to be done. Proper separation activities help with the next step of waste management. Waste can be temporarily stored within the laboratory area according to its type (Pribadi et al., 2020).

The chemical waste reduction practices in the list can be implemented in the PPLH IPB Lab, as shown in Table 4. The PPLH IPB Lab, as a testing laboratory, is fixated on testing standards, so it cannot replace the materials and testing methods. In contrast, educational and research laboratories can change their methods (Goh et al., 2019). Based on this, the PPLH Lab needs to streamline the use of chemicals by using them until the final product or entering the process of reuse, recycling, or recovery (Kernaghan et al., 2024).

Organic solvents used in various tests are very volatile, flammable, corrosive, toxic, and carcinogenic. Their use needs to be reduced or replaced with "green" solvents. However, green solvents have very restrictive criteria. Furthermore, testing laboratories adhere to standardized analytical protocols that restrict the substitution of solvents. Therefore, the implementation of on-site waste treatment and recycling is essential to extend the usable lifespan of solvents and improve overall resource efficiency (Fuente-Ballesteros et al., 2025).

Table 5 summarizes selected studies on the recovery, reuse, and recycling of laboratory chemical waste. Coletti et al. (2019) demonstrated that acetone waste can be recovered through distillation, achieving a purity of 99.84% with a recovery efficiency of up to 88%. Similarly, Zweckmair et al. (2017) reported solvent recovery of ethyl acetate with efficiencies reaching 90%. These findings indicate that solvent recovery is a viable alternative to disposal, as it can significantly reduce waste generation while maintaining relatively low operational cost (Aboagye et al., 2021).

Several studies have demonstrated the recovery of heavy metals, particularly silver, from laboratory waste (as shown in Table 5). Silver is commonly used in water quality testing, particularly for chloride determination using argentometric methods. This analysis generates heavy metal residues, primarily in the form of silver chloride (AgCl) and silver chromate (Ag_2CrO_4). Procedures for recovering silver from such residues have been established, notably by Steed and Hayes (1972) and can serve as a reference for laboratory waste recovery practices. The recovered silver can subsequently be converted into various value-added products, including microcrystalline silver for jewelry applications, silver nitrate ($AgNO_3$) for analytical use in chloride determination, and silver nanoparticles (AgNPs) for antimicrobial coating materials (von Dollen et al., 2018; Gatemala et al., 2017; Gusrizal et al., 2021). Given that silver is a relatively high-cost material, its recovery and reuse not only reduce disposal costs but also lower the need for chemical procurement or enable the production of high-value products (Goh et al., 2019).

Likewise, copper-based waste can be recover and reuse in the form of cuprous oxide (Cu_2O), which has been applied as a Fenton-like catalyst for the treatment of dye-contaminant (Rai, 2025). The recovery efficiency of Cu_2O has been reported to reach up to 97%, highlighting its potential for repeated use (Rai, 2025). By utilizing recovered materials to treat other waste streams, laboratories can enhance resource efficiency and move toward circular waste management practices. This approach supports the transition toward more sustainable and cost-effective laboratory operations and reinforces the importance of integrating recovery and recycling strategies into laboratory waste management systems (Goh et al., 2019).

Laboratory waste can be treated prior to disposal by reducing the toxicity of the generated liquid waste. One of the most widely applied approaches involves the removal of heavy metals from laboratory effluents. Various studies have investigated heavy metal removal using methods such as coagulation, precipitation, adsorption, bioremediation, electro-amalgamation, and hybrid treatment systems, as summarized in Table 6. Most of these treatment methods have demonstrated high performance, with removal efficiencies exceeding 90% (Ali et al., 2021; Callisaya et al., 2024; Dhenkula et al., 2025; Furtado et al., 2022; Loughlaimi et al., 2024; Suyasa et al., 2024; Wijayanti et al., 2022). The reduction of heavy metal concentrations prior to disposal not only decreases the volume and hazard level of waste requiring final treatment but also contributes to lowering disposal costs and minimizing health and safety risks during waste handling and transportation.

The final hierarchy in waste management is safe disposal. Safe disposal is achieved by working with third parties to manage waste that cannot be treated in the laboratory. Chemical waste containing mercury is toxic to public health and requires specific procedures; it can be sent to a licensed waste treatment company (Aji et al., 2025). Based on Ministry of Environment and Forestry Regulation No. 6 of 2021 concerning procedures and requirements for toxic waste management, it is known that it must be equipped with waste symbols and labels for the storage and packaging of toxic waste. An example of the toxic waste packaging symbol and label can be seen in Figure 4. In addition to preventing the mixing of incompatible chemicals in containers, information such as the type of waste and the period of waste generation must be noted on the label. The container is also given a maximum limit line of contents to remind the user when the container has been filled with more than 75% chemicals (Alam et al., 2021).

In its implementation, it is necessary to prepare a project scheme for changes in chemical waste management with discussions among laboratory managers. Discussions need to

Table 6. Several Studies About Waste Reduction Potential of Chemical Waste Treatment

Research	Chemical Waste Reduction Potential	Result	Reference
Coagulation			
Coagulation of heavy metals from laboratory waste	Heavy metals (Pb, Fe, and Cu)	Coagulation dose of 80 ppm can degrade the content of COD and TSS up to 99.8%	(Wijayanti et al., 2022)
Precipitation			
Neutralization, precipitation with sodium hydroxide (NaOH) and enhanced settling using coagulation-flocculation (alum + cationic polyelectrolyte)	Ag, Cr, Fe, and Hg	Removal efficiencies exceeded 90%	(Dhenkula et al., 2025)
Heavy metals from chemical analysis laboratory treated with chemical precipitation agent, calcium oxide (CaO)	Al, As, Cd, Cu, Fe	Removal efficiencies is 83.07–100%	(Loughlaimi et al., 2024)
Adsorption			
Adsorption using microparticles derived from Moringa oleifera seed husks (MS), cryogels of carboxymethyl cellulose (CMC), and hybrid cryogels combining CMC and MS (CMC-MS25 and CMC-MS50)	Cr^{6+}, Mn^{2+}, Co^{2+}, Fe^{3+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Sr^{2+}, Hg^{2+}, and Pb^{2+}	Utilizing CMC-MS25 and CMC-MS50 adsorbents resulted in the simultaneous removal of over 90% of the targeted metal ions	(Callisaya et al., 2024)
Adsorption using carboxymethyl cellulose (CMC), polydopamine (PDA), and sugarcane bagasse microparticles (BG)	Pb^{2+}	Removal efficiencies of Pb^{2+} is ∼97%	(Furtado et al., 2022)
Bioremediation			
Combining anaerobic bioaccumulation systems with sulfate reducing bacteria and phytoremediation with *Sansevieria trifasciata*	Pb, Cd, Zn, Cr, Cu	Heavy metals removal efficiencies is 94.78–99.51%	(Suyasa et al., 2023)
Electro-amalgamation			
Application of nickel-foam to reduce COD test waste	COD determination waste contains Hg, Ag, and Cr^{6+}	Maximum removal percentage of Ag, Hg, and Cr^{6+} were 100%, 99.8%, and 100%, respectively	(Ali et al., 2021)

be conducted to determine the most important changes, observations related to possible risks, cost budget plans, initiatives, ideas for developing activities, and waste management activities that can be carried out in the short and long term. An internal audit must be conducted after implementing chemical waste management in the laboratory. In an internal audit, observations are made for each failure, and then the cause and improvement plan that can be carried out are sought (Fuente-Ballesteros et al., 2025).

3.2.2 Proposed Laboratory Waste Management Roadmap

Based on the results of the gap analysis and the proposed action recommendations, a roadmap for laboratory waste management implementation was developed, as illustrated in the Figure 5. The roadmap is structured into three implementation stages: short-term, medium-term, and long-term. Actions that are immediately feasible are categorized under the short-term stage. Actions requiring additional time due to infrastructural limitations are placed in the medium-term stage, while those necessitating advanced infrastructure and facing regulatory constraints are classified as long-term.

As shown in the Figure 5, the roadmap comprises six phases of laboratory waste management across three implementation stages. Several phases require progressive advancement into subsequent stages. The immediate priority lies in ensuring regulatory compliance and control, and waste minimization. Compliance and control through the development of standard operating procedures (SOPs) for waste management are essential to minimize human error (Anaç et al., 2024). Improved labeling, including clear identification of waste categories and hazard types, is necessary to prevent the mixing of incompatible chemicals. Waste recording and reporting are crucial for tracking waste generation trends and supporting future evaluation and decision-making processes (Alam et al., 2021).

Optimization of chemical usage and the application of a first-in, first-out (FIFO) system can effectively reduce waste generation (Goh et al., 2019). The implementation of chemical exchange programs between laboratories is positioned in the medium-term, as it requires inter-institutional collaboration and the development of user-friendly systems accessible across organizations. Additionally, robust accounting and documentation systems are necessary to facilitate tracking and evaluation (Barbosa et al., 2020).

The phases of recovery, recycling, and onsite treatment are targeted for the medium- to long-term. In accordance with Ministry of Environment and Forestry Regulation No. 6 of 2021 concerning procedures and requirements for hazardous waste (B3) management, recovery and recycling activities require official permits, which may delay implementation. Furthermore, these processes demand additional infrastructure, requiring laboratories to allocate both capital investment and operational costs. As an initial step, pilot-scale implementation within laboratories is recommended, accompanied by cost–benefit analysis to evaluate the effectiveness of waste utilization strategies. Based on these findings, further discussions with management can be conducted to assess the feasibility of scaling up.

The phase of safe disposal, evaluation, and continuous improvement is initiated immediately and sustained throughout subsequent stages. Safe disposal involves ensuring proper waste segregation, secure transportation, and appropriate treatment by licensed third-party providers. As recovery, recycling, and in situ treatment are gradually implemented, it is essential to ensure that residual waste meets environmental health and safety standards. Periodic evaluation is conducted to assess the effectiveness of waste management practices and to identify areas for improvement (Akhdiyat et al., 2025).

4. CONCLUSIONS

This study provides a comprehensive evaluation of chemical waste management practices at a testing and calibration laboratory, revealing critical deficiencies in regulatory compliance, storage protocols, labeling systems, and recovery and recycling operations despite the presence of select minimization measures. Addressing these gaps, the study introduces a structured gap-to-roadmap framework that systematically integrates criteria-based gap identification, targeted action formulation, and phased implementation planning as a cohesive methodological contribution. These findings underscore the need for sector-specific, evidence-based frameworks that move laboratory waste management beyond mere compliance toward long-term environmental sustainability. However, that the proposed framework remains at the conceptual development stage; future research should therefore prioritize empirical evaluation of its implementation to validate its effectiveness, refine its applicability across diverse laboratory contexts, and strengthen the evidence base for its broader adoption.

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