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# Sustainable management of chemistry laboratory wastewater in undergraduate colleges: A review and way forward

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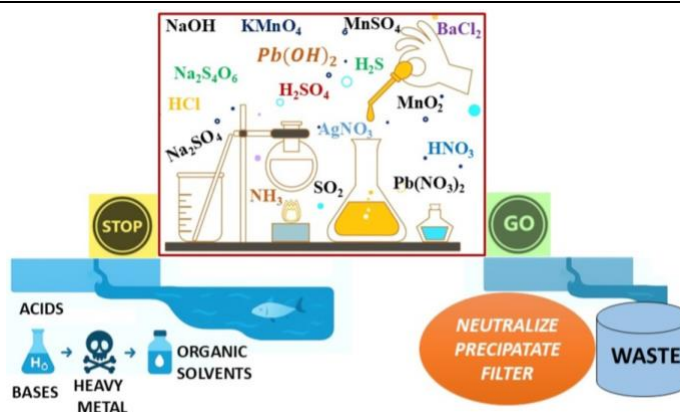
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## Keywords

Chemical laboratory  
Wastewater management  
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## Graphical abstract



## Highlights

- Undergraduate chemistry laboratories are a potential source of toxic wastewater.
- Discharge of untreated laboratory wastewater could pollute the environment.
- Low-cost, sustainable, and eco-friendly treatment strategies could be adopted.
- Neutralization, precipitation, and filtration techniques could effectively treat wastewaters.

## Abstract

Chemistry laboratories at undergraduate colleges play a vital role in teaching and research. These laboratories produce wastewaters containing hazardous substances, including strong acids, bases, heavy metals, and organic solvents. The disposal of untreated wastewater may pose risks to the environment and human well-being. This study aims to summarize types of laboratory wastewater, disposal practices, regulatory frameworks, and emerging sustainable alternatives. The emphasis was on low-cost, sustainable, and eco-friendly treatment strategies that could be easily adopted in undergraduate colleges with limited resources. This review highlights the need to integrate sustainable wastewater management practices into academic curricula to safeguard human and environmental health, ensure regulatory compliance, and support the broader goals of environmental sustainability. The integration of microscale experiments could considerably reduce the volume of hazardous liquid effluents. Deploying small-scale, on-site treatment facilities equipped with a combination of neutralization, precipitation, and filtration methods can serve as a preliminary decontamination step before final waste management options. Strengthening well-defined protocols for waste segregation, accompanied by methodical training for faculty members, students, and laboratory attendants, can emphasize secure laboratory practices. A coordinated approach involving policy initiatives, research advancements, and educational reforms will be a key to advancing eco-friendly and sustainable laboratory waste management practices across undergraduate institutions.

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## 1 Introduction

Laboratory-based teaching is central to science education, especially in subjects like chemistry, zoology, botany, and environmental science (Gericke et al., 2023). In these subjects, undergraduate curricula often incorporate laboratory sessions that utilize a wide range of chemicals, solvents, and biological materials (Jakubčínová et al., 2024). Although such experiments are indispensable for developing scientific competence and supporting theoretical learning, they produce substantial amounts of wastewater, often exhibiting corrosive, toxic, or biologically active properties (Bai et al., 2022; Dhenkula et al., 2025; Baliga et al., 2025). In contrast to major research centers or industrial laboratories equipped with advanced treatment facilities and waste management systems, most undergraduate colleges do not have advanced wastewater treatment facilities. As a result, wastewater generated in the laboratory is frequently released into public sewage networks without processing. Such actions may pose serious risks to both the environment and human health. These wastewaters often carry toxic heavy metals (e.g., mercury, lead, and chromium), halogenated organic compounds, persistent residues, and extremely acidic or alkaline solutions, which together pose threats to the environment.

To minimize the environmental impacts of laboratory wastewaters, the practical courses could adopt sustainability approaches, such as integrating green chemistry in undergraduate curriculum (Aubrecht et al., 2019; Shahzadi et al., 2025). However, instructors and laboratory staff often lack training in green chemistry or systematic waste segregation practices. Such inadequacies could lead to the overuse of chemicals and the accumulation of significant volumes of untreated laboratory wastewaters, despite the existence of safer micro-scale techniques that could serve as effective alternatives (Jain et al., 2021). Addressing such a problem is fundamental not only for safeguarding the environment but also for achieving commitments to global sustainability agendas such as the United Nations Sustainable Development Goals (UN SDGs) (Sharma et al., 2025). Specifically, it aligns with SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Nandi and Swain, 2024).

In India, adopting a green chemistry approach in the curriculum is challenging, partly due to poor awareness, limited financial support, and the absence of adequate technical expertise in most institutions outside centrally funded universities. Several state-aided and private colleges run under a limited budget, with emphasis placed on teaching

over infrastructure development. This leads to waste management, mostly concerning laboratory discharges, being given limited attention. The improper handling of chemical waste from laboratories may lead to pollution of local water bodies, deterioration of sewage systems, and increased occupational hazards for both students and personnel. The guidelines for handling hazardous waste laid down by the Central Pollution Control Board (CPCB) and the Ministry of Environment, Forest and Climate Change (MoEFCC) are primarily designed to address the needs of industrial sectors and high-level research institutions (Roy et al., 2025). When it comes to undergraduate colleges, there is a clear separation between existing policies and their on-ground execution. The current regulations rarely consider the budget limitations, shortage of staff, and academic focus typical of smaller institutions. As a result, administrators who intend to follow the guidelines repeatedly encounter challenges, and without rigorous oversight, unsafe disposal methods persist without control.

This review assesses the status of wastewater management systems in chemistry laboratories at undergraduate colleges in India. It evaluates the risks of chemical waste frequently produced, analyzes the effectiveness of current disposal systems, and highlights weaknesses in regulatory enforcement and infrastructure. The review incorporates case studies of successful practices, assesses cost-effective treatment approaches appropriate to undergraduate college laboratories, and suggests feasible, scalable strategies to enhance wastewater management at the institutional level.

## 2 Characteristics of laboratory wastewater

### 2.1 Inorganic chemistry laboratories

The characteristics of wastewater produced in chemistry laboratories differ significantly, determined by the experimental types. In an inorganic chemistry laboratory, chemical wastes are generated as a byproduct of routine experiments (Tables 1 and 2). Qualitative experiments use acids (HCl, H<sub>2</sub>SO<sub>4</sub>, and HNO<sub>3</sub>), bases (NaOH), and salts (e.g., AgNO<sub>3</sub>, BaCl<sub>2</sub>, and Pb(NO<sub>3</sub>)<sub>2</sub>). Quantitative analysis includes wastes generated from titrations involving KMnO<sub>4</sub>, Mohr's salt, sodium thiosulphate, and acid-base titrations (MnO<sub>2</sub>, MnSO<sub>4</sub>, Na<sub>2</sub>S<sub>4</sub>O<sub>6</sub>, NaOH, and Na<sub>2</sub>SO<sub>4</sub>).

### 2.2 Organic chemistry laboratories

The organic synthesis uses solvents (ethanol, acetone, ether, and benzene), acids, bases, and reagents (e.g., bromine and

acetic anhydride). Wastewater often includes organic residues, solvents, and acidic or basic waste. Purification and separation techniques generate waste from distillation, recrystallization, extraction (solvent waste), and chromatography.

### 2.3 Physical chemistry laboratories

Conductometry, potentiometry, and calorimetry experiments involve salt solutions and acids/bases, leading to ionic waste in water. Waste may be low in toxicity but still contributes to chemical loading (Goh et al., 2019).

### 2.4 Instrumental analysis laboratories

UV-Vis, IR, or colorimetry experiments typically involve dyes or chromophores (e.g., potassium dichromate and methylene blue). Waste may contain trace heavy metals and organic compounds.

## 3 Environmental and health impacts

### 3.1 Environmental impacts

The wastewater from the laboratories is chemically diverse and varies according to the curriculum design and the nature of the experiments (Table I). For instance, analytical chemistry laboratory curricula routinely utilize mercury compounds for electrode calibration, chromium (VI) in redox titrations (e.g., potassium dichromate), and lead salts in qualitative analysis. On the other hand, organic chemistry laboratory curricula involve the use of common organic solvents such as diethyl ether, chloroform, ethanol, and acetone in techniques like extraction, distillation, and recrystallization, often generating solvent-containing wastes (O'Neill et al., 2020; Milo et al., 2025).

The release of this wastewater to the environment without treatment can pollute both surface water and groundwater and endanger aquatic ecosystems (Jan et al., 2022; Hassan et al., 2025). For instance, bioaccumulation of heavy metals in aquatic ecosystems disturbs ecological

balance, weakens the food chain, and reduces biodiversity (Oros, 2025). Chromium (VI) hinders photosynthetic activity in aquatic flora and prevents nitrifying bacterial populations, mercury and lead tend to build up in aquatic species, especially fish, creating potential dietary and health hazards if consumed (Sharma et al., 2023). Likewise, improper disposal of mercury-containing reagents, often used in physical and analytical chemistry laboratories, induces mercury bioaccumulation in hydrobiological ecosystems (King et al., 2023). Long-term mercury exposure can cause neurological disorders and growing deficiencies (Wu et al., 2024). The release of acidic or basic waste can influence the pH of groundwater, leading to ecological loss and soil degradation. Organic solvents such as acetone, chloroform and ether usually enter drainage networks because of poor waste separation and insufficient solvent recovery measures. Because of their volatile nature, certain solvents evaporate into the atmosphere, deteriorating air quality and affecting ozone balance as well as climate dynamics. Improper disposal strategies may also stimulate dangerous reactions, giving off toxic fumes or, under severe conditions, sparking fires and explosions (Chandrappa and Das, 2024).

### 3.2 Health impacts

The exposure to untreated laboratory waste through breathing, swallowing, and bathing can be harmful (Wu et al., 2024). Long term exposure may lead to lung diseases, skin conditions, and neurological impairment, while extended exposure may increase the risk of cancer. The accumulation of toxic substances in food chains due to environmental pollution can lead to long-lasting health problems, including respiratory diseases, cancer, congenital malformations, and neurological disorders (Thakur et al., 2025). Mixed solid chemical waste, such as filter papers tainted with lead salts and organic dyes, is frequently discarded along with regular municipal waste. These substances release harmful gases and particulate matter upon burning, which add to polluted air and elevate the risk of respiratory illnesses among waste handlers (Baliga et al., 2025; Archana et al., 2025). Ineffective waste handling enhances institutional costs related to remediation and adherence to policy guidelines, whereas exposing students and staffs to chemical hazards (Abedsoltan and Shiflett, 2024). Poor laboratory waste

**Table I.** List of chemicals used in the chemistry laboratories, their types and hazard levels.

Chemicals	Type	Hazard level
HCl, and H <sub>2</sub> SO <sub>4</sub>	Acidic	Corrosive
NaOH, and NH <sub>4</sub> OH	Basic	Corrosive
Pb <sup>2+</sup> , Hg <sup>2+</sup> , Cd <sup>2+</sup> , and Cu <sup>2+</sup>	Heavy metals	Highly toxic
AgCl, and Fe(OH) <sub>3</sub>	Precipitates	Non-biodegradable
CH <sub>3</sub> COO <sup>-</sup> , and C <sub>2</sub> O <sub>4</sub> <sup>2-</sup>	Organic waste	Mildly toxic
SO <sub>2</sub> , H <sub>2</sub> S, and NH <sub>3</sub>	Gaseous by-products	Toxic or pungent fumes

**Table 2.** List of some chemicals and their hazard statements.

Chemicals	Hazard statements
Ethyl acetate	Highly flammable liquid and vapor
	Causes serious eye irritation
	May cause drowsiness or dizziness
	May cause respiratory irritation
Ammonia	Produces toxicity upon inhalation
	Causes severe skin burns and eye damage
	Very toxic to aquatic life
Hydrochloric acid	Causes severe skin burns and eye damage
	May be corrosive to metals
	May cause respiratory irritation
Sulfuric acid	Skin corrosion, eye irritation, organ-targeted toxic effects
	May be corrosive to metals
	May cause respiratory irritation
Silver chloride	Causes serious eye and skin irritation
	Very toxic to aquatic life with long lasting effects
	May be corrosive to metals
Sodium hydroxide	Causes severe skin burns and eye damage
	Harmful to aquatic life
Sulfur dioxide	Causes severe skin burns and eye damage
	Contains gas under pressure; may explode if heated

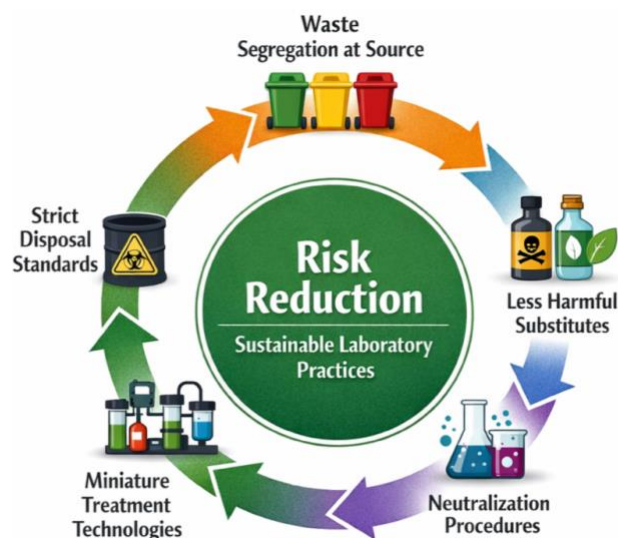
management degrades the institution's environmental compliance and sustainability credentials. Improper waste management is not just a theoretical distress but a tangible and multifaceted issue, representing documented environmental, human health, and economic impacts.

Inadequate training in waste management remarkably raises the risk of accidental spills, workplace accidents, and direct contact with hazardous chemicals (Anik et al., 2024; Tunç and Solmaz, 2025). Risk reduction can be fulfilled via sustainable laboratory practices such as dividing waste at the point of source, opting for less harmful chemical substitutes, employing neutralization procedures, adopting miniature treatment technologies, and strictly following disposal standards (Fig. 1). Integrating eco-friendly laboratory operations, maintaining appropriate waste labeling, showing regular inspections, and offering educational programs can significantly mitigate the impending harm to public health and the environment from chemical laboratory liquid waste (Phifer, 2024; Hashim et al., 2025).

Ineffective waste management threatens human health, destabilizes ecosystems, and reduces socio-economic

growth (Nurullah et al., 2025). In addition, inadequate waste management strains public finances, raising healthcare and remediation costs while harming ecosystem services (Adebayo, 2025). Poor waste disposal may lead to global warming by releasing methane and other greenhouse gases from landfill sites (Gupta et al., 2022). Inefficient handling of waste increases clean-up costs and disrupt ecosystems that support agriculture, fisheries, and tourism (Ansari et al., 2024). Consequently, poor waste management jeopardizes ecological balance and impedes sustainable development objectives.

Previous studies emphasized that the teaching laboratories release untreated liquid effluents directly into sinks and of dispose solid chemical residues with general waste (Kihampa and Hellar-Kihampa, 2015). For example, nearly 79% of chemistry laboratories in Nepal were identified to dump solid waste in regular bins, whereas 49% excreted chemical liquids into drains without neutralization, and over half were unsuccessful to separate organic wastes from inorganic ones (Kandel et al., 2017). Parallel trends were observed in developing countries, where poor infrastructure, insufficient storage, and the absence of formal



**Figure 1.** Circular approach to wastewater risk reduction from chemical laboratory in undergraduate colleges.

disposal structures impede safe waste handling (Debrah et al., 2022).

## 4 Wastewater management practices

### 4.1 Segregation at source

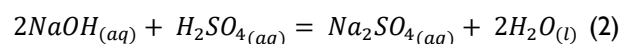
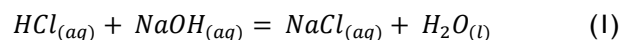
The efficient wastewater management begins at its sources (Fig. 1). This entails classifying chemicals by type and associated risks immediately after they are produced (Table 2). Wastes are usually classified as organic solvents, acids and bases, oxidizers, heavy metal by-products, and non-hazardous substances, and stored in clearly marked, color-coded containers (Neelam et al., 2025). Appropriate segregation reduces the risk of hazardous interactions between chemicals, ensures safer and more effective downstream processing, and assures adherence to environmental standards (Ho and Chen, 2018). In addition to strengthening safety, this approach lowers the likelihood of pollution and fosters students to adopt environmentally responsible habits.

### 4.2 Neutralization and precipitation

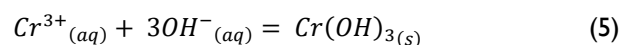
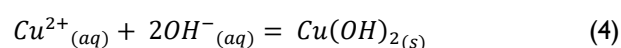
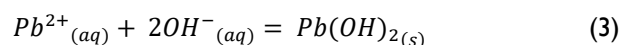
Neutralization and precipitation are the most useful techniques for reducing the hazards of chemical effluents prior to disposal (Alawa et al., 2022; Varshney et al., 2022). Neutralization process encompasses adjusting the pH of wastewater, whether acidic or alkaline, to a maintain pH between 6 and 8 (Jing et al., 2023). Precipitation is a process to eliminate dissolved contaminants, especially heavy metals,

by converting them into solid phases that can thereafter be extracted through filtration or settling. These methods are cost-effective and meet environmental regulations; however, their progress depends on correct waste separation, consecutive monitoring, and innocuous handling practices (Bwapwa and Bakare, 2021; Tripathy et al., 2025).

Neutralization reactions:



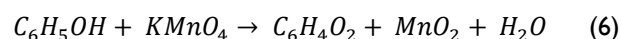
Precipitation reactions:



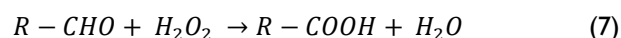
### 4.3 Chemical oxidation

Chemical oxidation is often used in undergraduate chemistry laboratories to neutralize detrimental organic pollutants. By employing oxidizing agents like potassium permanganate, hydrogen peroxide, or sodium hypochlorite, this process converts hazardous organic contaminants into environmentally friendly products, usually water and carbon dioxide (Huang et al., 2024). This method is most beneficial for treating resistant or harmful organic compounds. By decomposing these contaminants, chemical oxidation enhances the safety of wastewater treatment, minimizes environmental threats, and supports sustainable laboratory practices (Nidheesh et al., 2022).

Oxidation of phenol using potassium permanganate:



Oxidation of aldehydes with hydrogen peroxide:



Oxidation of organic waste using NaOCl:



### 4.4 Small-scale treatment units

Small-scale wastewater management units are installed to treat effluents at source. These systems include processes such as neutralization, filtration, precipitation, and adsorption to remove or lower contaminants, such as heavy metals, acids, and organic chemicals (Rezaei and Allahkarami, 2021). Compact treatment setups are cost-effective and manageable, making them ideal for institutions that produce

modest waste volumes. By addressing effluents at the source, they reinforce safety protocols and support green laboratory initiatives.

## 5 Green and sustainable approaches

To support sustainability and minimize environmental hazards, undergraduate chemistry laboratories can embrace cleaner wastewater management practices that also strengthen educational responsibility (de Oliveira et al., 2021; Freese et al., 2024). A major step in this direction is the introduction of microscale experiments, which greatly reduce reagent consumption and thereby minimize production of chemical waste (Verma et al., 2024). Green chemistry concepts are being integrated into curricula, promoting the replacement of hazardous reagents with biodegradable chemicals (Aubrecht et al., 2019). The wastes are separated into various groups, inorganic, organic, halogenated, and non-halogenated, so that they can endure proper treatment methods. Simple methods such as neutralization and precipitation are used to reduce the harmfulness of chemical effluents before disposal.

Sustainable laboratory management includes energy-efficient equipment, waterless condensers, and technologies such as closed-loop systems and cold traps that competently abate solvent evaporation and vapor emissions. These practices are reinforced through institutional efforts that comprise ongoing workshops and awareness campaigns, together with systematic updating of Material Safety Data Sheets (MSDS) to ensure chemicals are handled and disposed of safely (Anik et al., 2024; Abedsoltan and Shiflett, 2024). Experimental practices, such as the use of constructed wetlands and eco-reactors, are being explored in undergraduate colleges as decentralized treatment options (Wang et al., 2024). These improvements follow environmental standards and encourage students to adopt sustainable practices. Shifting to environmentally responsible strategies in chemistry education elucidates an adherence to teaching in line with global sustainability priorities.

## 6 Challenges and gaps

Many undergraduate chemistry laboratories face challenges in liquid waste management, mainly attributed to poor infrastructure, limited knowledge, and the lack of comprehensive institutional directives (Ramm et al., 2018; Banks et al., 2020; Hussein et al., 2022). The practice of combining laboratory effluents or releasing them directly into sinks contributes to environmental contamination and possible health hazards. A significant challenge appears from the inadequate arrangements for segregating various waste

categories, including solvents, acids, bases, and heavy metals. Neutralization or waste treatment infrastructure is absent in several educational institutions, and even where deployed, such systems are often poorly maintained, neglected, or ineffectively implemented because of financial and training constraints.

The insufficient incorporation of the green chemistry approach into present waste management practices remains an area of concern, as it could help prevent the exposure of harmful chemicals into the environment. Standardized protocols and monitoring mechanisms for safe waste management are missing, and both students and laboratory staffs often receive insufficient training for handling procedures (Rim and Lim, 2014). In other instances, records of waste generation are inadequately upheld or completely missing, which hinders both accountability and transparency. The problem is reinforced when institutions do not synchronize with disposal agencies (Kala and Bolia, 2024). In the absence of systematic policies, adequate funding, and effective enforcement, waste management systems remain inherently vulnerable and unsustainable. Mitigating these issues requires a concerted approach that includes policy revisions, enhanced infrastructure, training programs, and regular compliance checks (Aparcana, 2017).

## 7 Future perspectives

Ensuring safe and sustainable approaches will become crucial for dealing with liquid waste in undergraduate chemistry laboratories. By integrating microscale experiments and biodegradable compounds, laboratories can considerably reduce the volume of hazardous liquid effluents. Deploying small-scale on-site treatment facilities equipped with a combination of neutralization, precipitation, and filtration methods can serve as a preliminary decontamination stage prior to final waste management. Strengthening well-defined protocols for waste segregation, accompanied by methodical training sessions for faculty and students, can emphasize secure laboratory practices. The utilization of digital platforms to track and record waste generation supports transparency and compliance to regulations, while collaboration with certified waste disposal agencies and monitoring bodies confirms appropriate off-site treatment. Providing financial support and integrating environmental safety into the curriculum can support responsible practices in chemical use. In the long run, a coordinated approach involving policy initiatives, research advancements, and educational reforms will be key to advancing eco-friendly and sustainable laboratory waste management across undergraduate institutions.

## 8 Conclusion

In undergraduate colleges, effective management of chemical wastes is crucial to maintain environmental integrity and safeguard human well-being. In undergraduate chemistry laboratories, proper wastewater management is required to ensure safety and environmental protection. These approaches profoundly limit chemical consumption and the production of waste. Incorporating sustainable practices and inexpensive treatment technologies provides practical solutions for undergraduate colleges with limited resources. Moreover, educational and training initiatives encourage students and faculties to develop responsible laboratory habits. These efforts strengthen sustainable laboratory practices and help to minimize ecological threats.

## 9 Data availability statement

This is a review article, and the data are publicly available as published materials cited in this manuscript.

## 10 Ethical statements

Not applicable.

## 11 Acknowledgement

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## 12 Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## 13 Author contributions

A.K. Kundu: Conceptualization, and writing – original draft. M. Habib: Writing – review & editing. M. Mandal: Writing – review & editing. All authors approved the final version of the manuscript.

## 14 Copyright statement

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