International Journal of Multidisciplinary Research and Growth Evaluation.

Ferdowsi University Mashhad/ The second International Conference
Artificial Intelligence: Between Scientific Innovation and Human Responsibility

A Review of Biological and Chemical Hazards in Academic and Research Laboratories: Public Health Risks and Perspectives on Sustainable Development

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Article Info

ISSN (Online): 2582-7138
Impact Factor (RSIF): 7.98
Volume: 06
Issue: 06
November - December 2025
Received: 15-09-2025
Accepted: 16-10-2025
Published: 23-11-2025
Page No: 208-216

Abstract
Scientific laboratories play a crucial role in advancing education, research, and technological innovation; however, they also present significant chemical and biological hazards that can threaten both human health and the environment. These hazards may include carcinogenic, toxic, and corrosive substances, as well as pathogenic microorganisms and laboratory wastes capable of contaminating soil, water, and air if mismanaged. This article explores the nature, sources, and potential impacts of biochemical hazards within laboratory environments, emphasizing the importance of implementing effective safety practices—such as rigorous biosafety protocols, chemical hygiene procedures, and responsible waste management—to minimize risks and safeguard health and sustainability. Also underscores the importance of adopting green chemistry principles and sustainable laboratory practices to lessen environmental impacts, cut down on hazardous waste, and preserve natural resources. Aligning laboratory activities with sustainability frameworks directly supports several Sustainable Development Goals (SDGs), particularly those related to good health, clean water, and responsible consumption. Strengthening a culture of laboratory safety—through continuous training, thorough risk assessments, and strict policy enforcement—is essential to ensure safe research environments and advance scientific progress in an environmentally responsible manner.

DOI: https://doi.org/10.54660/.IJMRGE.2025.6.6s.208-216

Keywords: 2030 Agenda, Laboratory safety, Bio-Chemical Risks, CBRN, Environmental Health, Green chemistry

1. Introduction

Since the mid-20th century, research laboratories have undergone remarkable transformation, evolving into dynamic centers of interdisciplinary innovation (Council, Affairs, Education, & Universities, 2012) [13]. These environments, once primarily focused on industrial chemistry, have evolved to encompass a wide range of advanced disciplines, including genetic engineering, microbiology, analytical chemistry, and nanotechnology. The foundation of laboratory safety lies in the early identification of potential workplace hazards. Generally, occupational risks in such settings are classified into three principal categories: chemical, biological, and physical hazards.

The sources of chemical hazards encompass a wide range of substances, including paints, solvents, compressed gases, pharmaceutical preparations, cleaning and disinfecting agents, and anesthetic vapors. Improper handling of these materials can result in severe risks, particularly during their use, transport, or storage under unsafe conditions. Modern laboratories have undergone significant advancements in complexity, evolving beyond simple experimental stations into high-risk environments where personnel are routinely exposed to diverse chemical and biological hazards. This reality underscores the critical importance of implementing strict safety management practices and adopting effective preventive strategies. (Wang, Su, Cao, & Li, 2025) [55]. These include infectious agents, carcinogens, volatile compounds, and corrosive materials that pose serious threats to human and environmental health. In 2008, a tragic incident at the University of California, Los Angeles (UCLA) led to the death of a research assistant following an accident involving pyrophoric tert-butyllithium (Shu, Li, & Gao, 2023) [51]. A similar tragedy occurred in 2015 when a hydrogen gas explosion claimed the life of a postdoctoral researcher at Tsinghua University (Baudendistel, 2009) [9]. In 2018, an explosion of a high-pressure hydrogen cylinder at the Indian Institute of Science in Bengaluru, India, also resulted in the loss of a young researcher. Beyond the profound personal toll, such incidents tarnish the reputations of academic institutions and disrupt scientific progress. These recurring accidents highlight the urgent need for rigorous safety protocols, robust risk management strategies, and the cultivation of a strong safety-oriented culture within research laboratories. (A Dana Ménard & John F Trant, 2020) [33]. With the increasing complexity of laboratory operations—particularly in fields such as veterinary research—safety has evolved from a mere procedural requirement into a strategic institutional priority. Veterinary laboratories play a crucial role in monitoring environmental hazards, ensuring food safety, and promoting animal health [6]. However, their frequent use of biological agents and chemical reagents introduces a broad spectrum of risks that extend beyond the confines of the laboratory. Improper handling or disposal of these materials can lead to serious consequences, including public health emergencies, environmental pollution, and the transmission of zoonotic diseases. (Baudendistel, 2009) [9]. In response to these challenges, international and national organizations such as the World Health Organization (WHO), the Occupational Safety and Health Administration (OSHA), and the Centers for Disease Control and Prevention (CDC) have developed comprehensive biosafety frameworks. These guidelines establish standardized safety practices and classify laboratories according to defined biosafety levels (BSL), ensuring that the degree of containment and protective measures corresponds to the potential risk associated with the biological agents being handled. (Cuming, Rocco, & McEachern, 2008; Desa, Habidin, Hibadullah, Fuzi, & Zamri, 2013; A. D. Ménard & J. F. Trant, 2020) [14, 15, 33]. Robust laboratory protocols for detection, containment, and decontamination are indispensable within the broader framework of Chemical, Biological, Radiological, and Nuclear (CBRN) threats. In such contexts, biosafety and biosecurity frameworks gain heightened relevance, as they provide the structural foundation for mitigating risks, ensuring rapid response, and maintaining operational safety in laboratories that may encounter high-consequence hazardous agents. (Kako, Hammad, Mitani, & Arbon, 2018) [23]. Laboratory personnel, particularly in veterinary and public health domains, often operate at the frontlines of biodefense, epidemiological surveillance, and chemical risk mitigation. Despite the widespread availability of safety guidelines, the integration of these practices into broader sustainability agendas remains underdeveloped (Organization, 2004) [40]. The United Nations' 2030 Agenda for Sustainable Development outlines 17 goals aimed at promoting peace, prosperity, and environmental responsibility. Several of these goals intersect with laboratory practices, where sustainable management—through resource efficiency, waste reduction, and green technologies—supports key objectives such as health (SDG 3), clean water (SDG 6), responsible consumption (SDG 12), and climate action (SDG 13). (Lee *et al.*, 2016) [29]. SDG 3 (Good Health and Well-being) emphasizes the reduction of occupational hazards and Several SDGs relate to laboratory operations: SDG 6 promotes proper chemical and wastewater management, SDG 12 encourages minimizing hazardous waste, and SDG 8 supports safe and secure working conditions for laboratory personnel. (Palmer, 2015) [42]. Additional SDGs are also relevant to laboratory sustainability. SDG 9 (Industry, Innovation, and Infrastructure) promotes the development of resilient and sustainable scientific infrastructure, while SDG 13 (Climate Action) encourages the establishment of low-emission, energy-efficient laboratory systems that contribute to climate resilience and environmental protection. (Gasper, 2019) [19]. These objectives are much more pertinent in the context of veterinary science. Veterinary laboratories are situated in the nexus of public health, environmental protection, and sustainable development because they handle a variety of chemical and biological materials in research, diagnostic, and surveillance activities. (Gasper, 2019; Leal Filho *et al.*, 2019) [19, 28]. If the inherent risks within these environments are not properly managed, they may hinder progress toward achieving sustainable development, compromising both environmental integrity and public health. (Leal Filho *et al.*, 2019) [28]. This review demonstrates that laboratory-related biochemical hazards in veterinary practice significantly affect SDG 3 (Good Health and Well-Being**),** SDG 6 (Clean Water and Sanitation)**,** SDG 12 (Responsible Consumption and Production)**,** and SDG 15 (Life on Land)**.** Addressing and mitigating these risks is not only vital for ensuring worker safety but also represents a deliberate step toward advancing the United Nations' 2030 Agenda and integrating veterinary science within the broader framework of global sustainability.

(Kasima, Mugonola, Menya, Ndaula, & Ndyomugyenyi, 2025) [24]. Furthermore, incorporating sustainability into laboratory operations aligns with emerging frameworks such as biosafety by design and green chemistry. These approaches advocate for the use of safer materials, the minimization of waste, and the adoption of ethical experimental practices that reduce adverse impacts on both the environment and public health. (Schneider *et al.*, 2019). . The global crisis brought renewed attention to biosafety procedures, disease containment, vaccine research, and biomedical waste management. To effectively address emerging threats, existing safety standards must be revised to reflect the increasing use of genetically modified organisms (GMOs) in research. The COVID-19 pandemic underscored the pivotal role of laboratories in scientific advancement, public health preparedness, and biological risk management, firmly establishing them as key contributors to global sustainability and resilience. (El-Hani & Machado, 2020 [16]; "Swelling behavior of poly (AAM_MA) hydrogel matrix and study effects PH and ionic strength, enforcement in controlled release system,"). This experience reinforced the notion that laboratory safety is not solely a local or institutional con cern but a fundamental component of global sustainable development efforts (Bai *et al.*, 2022) [6]. Furthermore, Agenda 21-particularly relevant in the context of developing nations-has identified two major obstacles to effective chemical risk management:

(1) inadequate scientific data for accurate risk assessment, and

(2) limited technical and financial resources to evaluate chemicals even when data exist.

These barriers highlight the pressing necessity for a more integrated framework that links laboratory safety practices with sustainable development strategies, ensuring that environmental protection, occupational health, and scientific improvement advance together in harmony (Risheng, 2012) [48].

This Review Therefore aims to

- Identify the main biological and chemical hazards present in laboratory environments, particularly within veterinary contexts;
- Evaluate current mitigation strategies and safety protocols in practice; and
- investigate how effective management of laboratory hazards contributes to achieving the objectives of the United Nations 2030 Agenda for Sustainable Development.

By pursuing these goals, this paper underscores the urgent need to establish a comprehensive framework that integrates chemical hygiene, environmental responsibility, and biosafety (Abdel Salam, Abukhadra, & Adlii, 2020; O'Neil, Scott, Relph, & Ponnusamy, 2020) [1, 38]. It outlines important risk factors and suggests focused strategies for management and prevention by methodically analyzing both current and emerging hazards. Protecting laboratory workers, protecting priceless resources, and maintaining the integrity of scientific research all depend on such measures. Additionally, this review aims to reduce the frequency of laboratory accidents and their wider societal effects while advancing sustainable and responsible scientific innovation through the promotion of a pervasive culture of safety.

2. CBRN Hazards in Laboratory Environments

Chemical, Biological, Radiological, and Nuclear (CBRN) diagnostic laboratories occupy a distinctive position at the intersection of public health, national security, and scientific research. Laboratory operations that involve hazardous biological agents, high-energy materials, or radioactive isotopes are integral to the CBRN framework, which serves as a critical foundation for emergency preparedness, risk mitigation, and defense strategies. (Maciejewski, Gawlik-Kobylińska, Lebiedź, Ostant, & Aydın, 2020) [32]. Chemical hazards in laboratories include explosive reagents and volatile organic solvents, whereas biological hazards encompass pathogenic microorganisms and genetically engineered organisms. Both categories pose significant threats to laboratory personnel and the environment, necessitating strict adherence to biosafety and chemical hygiene protocols to ensure safe and sustainable research practices. (Calder & Bland, 2018) [11]. The laboratory use of radioactive isotopes in energy, environmental, and medical research can give rise to radiological and nuclear hazards. Improper handling of these materials may lead to acute radiation exposure, long-term environmental contamination, and even global biosecurity risks. Therefore, rigorous control measures, radiation monitoring, and waste management protocols are essential to ensure both worker safety and environmental protection. (Calder & Bland, 2018) [11]. To maintain accountability and containment of hazardous agents, laboratories operating in CBRN-sensitive domains must follow stringent protocols controlling material inventory, incident reporting, and waste management. Maintaining adherence to established public health and security standards requires cooperation with national and international regulatory agencies. Additionally, incorporating CBRN readiness into safety training, operational procedures, and laboratory design—through exercises like lockdown drills, decontamination, and dual-use research supervision—significantly increases institutional resilience against both unintentional and deliberate threats. (GOGACZ, 2024). Integrating CBRN safety with sustainability is crucial not only for preventing catastrophic incidents but also for minimizing chronic exposure risks and long-term environmental harm. Such integration directly supports several Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 16 (Peace, Justice, and Strong Institutions), reinforcing the essential connection between laboratory resilience, public safety, and sustainable development.(Gawlik-Kobylińska, 2022).

Fig 1: Chemical, Biological, Radiological, and Nuclear Hazards

2. Biological Hazards

Biological hazards (biohazards) refer to toxins, bacteria, viruses, fungi, parasites, and other harmful biological agents that pose a threat to human health. Such risks are particularly prevalent in laboratories engaged in clinical diagnostics, microbiology, molecular biology, and biotechnology, where exposure to infectious materials and biological specimens is routine. Effective biosafety measures and containment practices are therefore essential to prevent accidental infections and ensure laboratory and environmental safety. (Mourya, Yadav, Majumdar, Chauhan, & Katoch, 2014). Researchers may be exposed to biological hazards through several routes, including ingestion of hazardous agents, direct contact with contaminated materials or surfaces, inhalation of infectious aerosols, and accidental needlestick injuries. To mitigate these risks, laboratories implement strict biosafety measures, encompassing the use of personal protective equipment (PPE), containment practices, and proper waste management. The World Health Organization (WHO) classifies laboratories into Biosafety Levels (BSL-1 to BSL-4) based on the pathogenicity, transmissibility, and potential impact of the biological agents handled, thereby ensuring that safety protocols are appropriately matched to the level of risk. (Mourya *et al*., 2014). Control measures include using biosafety cabinets, personal protective equipment (PPE), proper sterilization, effective waste management, and mandatory biosafety training to minimize exposure and ensure safe laboratory practices. (Kumar, Kumar, & Das, 2025). Following these guidelines is crucial for researcher safety as well as for avoiding environmental contamination and laboratory-acquired infection outbreaks. (Organization, 2004) [40].

3. Chemical Hazards

Among the most frequently encountered risks in laboratory settings are chemical hazards, which encompass a diverse array of hazardous substances ranging from toxic compounds like formaldehyde and carcinogenic agents such as benzene to mutagenic materials, corrosive chemicals, flammable substances, and compounds exhibiting high reactivity. (Bassam, Noleto-Dias, & Farag, 2022). Exposure to such hazardous substances may occur through various routes of entry, namely inhalation, dermal penetration, ingestion, or eye contact, all of which constitute substantial threats to laboratory personnel wellbeing. Comprehensive risk reduction approaches encompass the implementation of Safety Data Sheets (SDS) for hazard communication, adoption of the Globally Harmonized System (GHS) for uniform chemical labeling, deployment of localized exhaust ventilation infrastructure including fume hoods, and rigorous adherence to established Standard Operating Procedures (SOPs). Adequate training and continuous enforcement of safety measures are vital for preserving laboratory safety and preventing exposure-related incidents among workers. Chemicals entering the environment pose severe and persistent health risks by contaminating air, water, and soil systems. Beyond disrupting ecological balance, such contamination presents serious dangers to human health and wildlife populations. Many chemical agents exhibit toxic properties that can trigger health problems ranging from acute immediate reactions to chronic long-term conditions. The extent of harm is governed by several interconnected factors: the chemical's toxic nature, exposure level, and entry pathway into the body—whether inhaled, swallowed, or absorbed through skin. Heavy metals such as lead and mercury provide clear examples of substances well-known for their severe health impacts. (Hormozi, Laal, Hejazi, Dalakeh, & Ashouri, 2025; Zwickl *et al*., 2022) [22]

5. Linking Laboratory Safety with Sustainable Development

The integration of laboratory safety protocols with the principles of sustainable development reveals the critical role that scientific facilities play in achieving universal sustainability targets. Comprehensive laboratory safety frameworks contribute substantially to the realization of several Sustainable Development Goals established by the United Nations. Specifically, these safety measures support SDG 3 (Good Health and Well-Being) by establishing protective work environments that reduce occupational health risks and prevent laboratory-acquired infections among research personnel. They advance SDG 6 (Clean Water and Sanitation) by implementing proper waste disposal systems that prevent chemical and biological agents from contaminating water resources and surrounding environments. Laboratory safety initiatives further promote SDG 9 (Industry, Innovation and Infrastructure) by encouraging the research, development, and implementation of green technologies and safer laboratory equipment. Alignment with SDG 12 (Responsible Consumption and Production) occurs through the adoption of practices such as chemical minimization strategies, waste recycling programs, and green chemistry methodologies that reduce hazardous substance usage. (Lull, Bautista, Lidón, & López-Paz, 2021; S. Rai, Sriram, & Alva, 2024) [31, 44]. Environmental stewardship is demonstrated through SDG 13 (Climate Action) as laboratories implement sustainability plans designed to reduce greenhouse gas emissions stemming from chemical processes and energy-intensive operations. Finally, laboratory safety contributes to SDG 16 (Peace, Justice, and Strong Institutions) by necessitating strong governance structures for overseeing dual-use research with potential security implications and managing Chemical, Biological, Radiological, and Nuclear (CBRN) materials. This multifaceted alignment positions laboratory safety as an essential component of the global framework for sustainable and responsible scientific progress (Blasi, Ganzaroli, & De Noni, 2022).

5.1. SDG 6 – Clean Water and Sanitation

A basic human right and the foundation of public health is access to clean, safe water. If trash is not adequately managed, laboratories—especially those that deal with biological agents and dangerous chemicals—pose a risk to water systems. (Baskaran, 2022). Improper disposal of biological cultures, organic solvents, heavy metals, and pharmaceutical residues can lead to the contamination of surface and groundwater, posing serious risks to both human health and ecosystems. Ensuring safe waste disposal, effective wastewater treatment, and strict compliance with hazardous waste regulations is therefore crucial to preventing environmental degradation and protecting public health. (Zindi & Shava, 2022). SDG 6 (Clean Water and Sanitation) is advanced through sustainable laboratory measures such as using biodegradable chemicals, adopting closed-loop water systems, and ensuring proper waste segregation. Integrating chemical hygiene and biosafety practices supports global water protection efforts. Yet, growing population, urbanization, and climate change continue to strain freshwater resources, emphasizing the need for sustainable water management in laboratories. (Shehu & Nazim, 2022). Moreover, the agricultural sector's growing dependence on irrigation for food production, combined with the need to safeguard ecosystems and preserve biodiversity, further intensifies pressure on global water resources. (Rajapakse, Otoo, & Danso, 2023). Socioeconomic activities that increase demand and contaminate existing supplies exacerbate climate-related disturbances to freshwater supply and aquatic habitats. (Küfeoğlu, 2022). Sustainable Development Goal 6 (SDG-6) sets forth both governance and technology-driven targets aimed at ensuring universal access to clean water and adequate sanitation, promoting efficient management and sustainable use of water resources worldwide. (Arora & Mishra, 2022). Achieving these goals is vital for water security and for advancing interconnected objectives such as SDG 2 (Zero Hunger) and SDG 14 (Life Below Water), thereby contributing to the protection of the planet's ecological balance and future sustainability. (Thompson & Bunds, 2022). Water is fundamental to environmental integrity, agricultural productivity, human health, and broader sustainability efforts. Achieving sustainable water use requires minimizing waste and promoting water reuse through circular management systems that optimize conservation and resource efficiency. (Küfeoğlu, 2022).

5.2 Microbial Hazards and Water Contamination: Advancing SDG 6 in Laboratory Settings

Among the most serious biological hazards encountered in laboratories—particularly in microbiology and veterinary research—are microorganisms such as bacteria, viruses, fungi, and parasites. Inadequate biosafety practices can lead to laboratory-acquired infections and broader environmental contamination through accidental exposures or improper disposal of microbiological waste. (Organization, 2021) [41].

One of the most concerning outcomes of poor biosafety and waste management is the release of microbiological agents into water systems, especially when untreated or inadequately treated wastewater is discharged. In rural or low-resource areas lacking effective wastewater infrastructure, pathogens such as Escherichia coli and Leptospira spp. can persist in aquatic environments, leading to outbreaks of waterborne diseases that pose severe threats to both human and animal health. This underscores the importance of integrated biosafety measures, wastewater treatment, and environmental monitoring as essential components of sustainable laboratory operations aligned with SDG 6. (Li, Saleem, Edge, & Schellhorn, 2021). The prevention of microbial contamination in water systems necessitates that laboratories establish holistic management frameworks incorporating several critical elements: systematic pre-treatment and sterilization protocols for microbiological wastewater, stringent segregation practices to maintain distinct biological and chemical waste pathways, and complete conformity with applicable national environmental legislation and biosafety guidelines. The execution of such protective measures serves dual purposes—mitigating potential ecological damage and public health threats while simultaneously reinforcing the laboratory's active participation in sustainable water stewardship and the realization of SDG 6.(M. S. K. Rai, 2024)

The mitigation of microbial risks within laboratory facilities constitutes a direct contribution to achieving Sustainable Development Goal 6 (Clean Water and Sanitation), while concurrently advancing complementary targets such as SDG 3 (Good Health and Well-being) and SDG 15 (Life on Land). Proper management of microbial waste streams transcends the boundaries of occupational health and safety, representing a comprehensive commitment to safeguarding public health and ensuring environmental sustainability on a broader societal scale. (Aman *et al*., 2024).

5.3. Green Chemistry and Sustainable Chemical Management in Laboratory Environments

Green chemistry focuses on designing chemical products and laboratory processes that minimize or entirely eliminate the use and generation of hazardous substances. This approach not only protects public health but also enhances resource efficiency, promoting the sustainability and competitiveness of the chemical industry. Implementing green chemistry principles in laboratory settings is therefore crucial for preventing environmental pollution, reducing chemical waste, and conserving natural resources, aligning scientific practice with global sustainability goals.(Arora & Mishra, 2022).Chemicals are indispensable to industrial progress and the improvement of human life, yet their improper handling and disposal can pose severe threats to both ecosystems and human health. The severity of these risks depends on factors such as the level and duration of exposure and the chemical's inherent properties and structure. According to Chang and Lamm (2003)**,** the hazards associated with chemical exposure arise not only from a substance's toxic potential but also from its interactions with biological **and environmental systems**, highlighting the critical need for stringent control measures and sustainable chemical management practices..(Chang, Flatau, & Liu, 2003), the mismanagement of hazardous laboratory chemicals remains a persistent challenge that necessitates proactive intervention and policy enforcement. This aligns with the broader principle that environmental sustainability must be addressed at the molecular level, where chemical reactivity, stability, degradability, and ecological persistence are determined. (Rajapakse *et al*., 2023) A wide range of chemical agents, such as metal-based reagents, synthetic dyes, organic solvents, potent oxidizers, and surfactants, are commonly used in scientific labs. Numerous of these compounds have high levels of biological activity and environmental stability, which can have long-term ecological effects like oxidative stress, microbial community disruption, bioaccumulation in food chains, and genotoxicity in non-target organism (Evaristo *et al*., 2023). Thus, chemical selection should be informed not only by experimental performance but also by Life Cycle Assessment (LCA**)**, biodegradability indices, and ecological toxicity thresholds.

To mitigate these risks, several strategies can be integrated into laboratory workflows

- Substituting hazardous solvents with water-based or bio-derived alternatives.
- Employing micro-scale experiment designs to reduce reagent consumption and waste volume.
- Implementing solvent recovery and closed-loop liquid handling systems to prevent direct discharge.
- Utilizing biodegradable and non-bioaccumulative dyes, surfactants, and polymeric agents.
- Managing metal-containing waste streams to prevent chelation-driven mobilization of heavy metals into ecosystems.

Over the past decade, Green Laboratory Programs have achieved remarkable progress in integrating the principles of green chemistry and occupational safety into academic and research environments. The widespread implementation of the se initiatives in universities, research centers, and biopharmaceutical laboratories reflects a growing global commitment to minimizing the environmental impact of laboratory activities. As a result, many institutions have reported significant reductions in energy and water consumption, as well as noticeable declines in the generation of chemical and solid waste. (Tomlinson *et al*., 2021). According to recent assessments, laboratories that have implemented green laboratory frameworks have seen significant decreases in the production of hazardous waste and a 30–60% reduction in energy consumption (Ramos *et al*., 2022; Liu & Barrett, 2023) (Ramos & Vicente, 2024). These results highlight how integrating sustainability-driven practices into lab infrastructure has both operational and environmental advantages. One obvious example is shutting off the chemical fume hood sash when not in use, which greatly lowers the energy requirements of ventilation systems and limits researcher exposure to chemical emissions. By encouraging safe chemical storage, efficient hazardous waste management, and reducing exposure to physical risks like UV radiation and other laboratory hazards, green laboratory initiatives strengthen this strategy even more.

6. The Role of Laboratory Hazard Management in Advancing the UN 2030 Agenda

Effective management of laboratory hazards plays a critical role in supporting the achievement of several United Nations Sustainable Development Goals (SDGs) under the 2030 Agenda.(Aithal & Aithal, 2021) Laboratories, particularly in the biomedical and veterinary sectors, often handle a wide array of biological, chemical, and radiological agents. If mismanaged, these materials can pose serious risks to human health, environmental integrity, and social well-being. Implementing robust safety protocols—such as biosafety level classification, chemical hygiene plans, and waste treatment systems—directly contributes to SDG 3 (Good Health and Well-being) by protecting researchers and surrounding communities from occupational exposure and disease transmission. Furthermore, responsible waste management and the reduction of hazardous discharges align with SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) (Fong & Chiu, 2024; Khan). By minimizing laboratory emissions, energy use, and toxic byproducts, institutions also contribute to SDG 13 (Climate Action). Integrating safety with sustainability transforms laboratory practices into models of responsible innovation and environmental stewardship, ultimately reinforcing global commitments to sustainable development and public health protection (Ramzan, Ullah, Raza, & Nadeem, 2023).

7. Challenges in Achieving SDG 6 in the Context of Biological and Chemical Hazards

Achieving SDG 6 in laboratory settings remains a complex endeavor, especially in environments where both biological and chemical hazards are present (Gawlik-Kobylińska, 2022). A primary challenge is the lack of awareness among laboratory personnel regarding the environmental consequences of improper waste handling. This includes not only chemical substances but also biological waste, such as microbial cultures, pathogenic materials, and genetically modified organisms, which can pose significant risks to water safety if not properly neutralized (Mohan, Robinson, Vodwal, & Kumari, 2024). A significant percentage of laboratory facilities, especially those located in resource-constrained environments, exhibit insufficient expertise in crucial areas such as waste categorization and segregation, sterilization techniques, and environmentally friendly operational procedures. This lack of training frequently leads to the direct or unintentional introduction of dangerous chemical and biological agents into municipal wastewater systems, increasing the risks of toxic residue accumulation and the spread of pathogenic organisms in both surface water bodies and subsurface aquifer systems. The predicament is exacerbated by infrastructural deficiencies, as considerable numbers of academic research and clinical diagnostic laboratories operate without adequate wastewater treatment capacity, particularly concerning microbiological effluent processing. Furthermore, persistent legislative and regulatory lacunae, coupled with inadequate enforcement mechanisms for environmental statutes pertaining to laboratory waste discharge, represent formidable barriers to achieving sustainable and biosafe laboratory management practices. (Abia, Baloyi, Traore, & Potgieter, 2023).

Other pressing barriers include

- The high cost of installing water purification and sterilization systems.
- Limited adoption of green chemistry and biosafety by design.
- Resistance to change within institutional cultures that prioritize scientific output over environmental responsibility.

Without coordinated investments in training, infrastructure, and regulatory oversight, laboratories will remain a critical source of water pollution, (Omohwovo, 2024) hindering global efforts to ensure clean water access. Addressing these challenges—especially the safe handling of microbial and chemical hazards—is essential for laboratories to become active contributors to sustainable water management and to the fulfillment of SDG **6** and related public health goals. (Nguyen *et al*., 2021) fig (3) Key Barriers to Sustainable Laboratory Waste Management.

Fig 2: Challenges in Implementing Eco-Friendly Laboratory Practices

8. Future Directions

The advancement of sustainable laboratory practices necessitates a multifaceted strategic approach encompassing several key priorities for future development. These include the systematic integration of green chemistry methodologies to minimize hazardous substance use, substantial investment in state-of-the-art waste treatment technologies capable of neutralizing or recovering hazardous materials, and the widespread adoption of closed-loop water circulation systems that reduce resource consumption and environmental discharge. To guarantee that biosafety laws are in line with the more general sustainable development objectives embraced by the global community, it is equally crucial to fortify national policy frameworks. A proactive and flexible approach to biosafety governance can be fostered by integrating cutting-edge digital technologies, especially artificial intelligence-based risk monitoring and predictive analytics systems, which have great potential to improve operational efficiency and regulatory compliance across laboratory networks. Complementing these technological advances, targeted professional training programs and strengthened international collaborative networks will serve as foundational pillars for establishing a unified global safety culture aligned with the United Nations 2030 Agenda for Sustainable Development. In the specific context of radiation safety governance, national governments bear the responsibility of enacting comprehensive legislation that articulates safety and protection requirements applicable to all radiation exposure contexts, whether occupational, medical, or public. This legislative framework must explicitly designate primary responsibility to the operators and license holders of radiation-generating facilities and activities. To ensure effective oversight, an independent regulatory authority must be established with well-defined statutory powers enabling it to monitor, inspect, and enforce compliance with radiation protection standards without undue political or commercial influence. The enabling legislation must precisely define the regulatory scope and establish formal coordination protocols among relevant governmental agencies to facilitate an integrated and coherent approach to radiation risk management across all sectors.

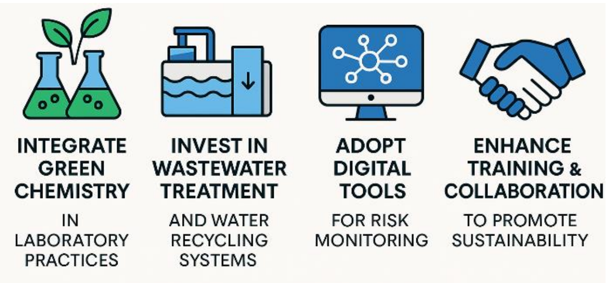

Fig 3: Strategies for Sustainable Laboratory Management

9. Conclusion

Laboratory safety is a foundational component of sustainable scientific practice. Effective management of biological and chemical hazards protects laboratory personnel, prevents environmental contamination, and strengthens the reliability and integrity of scientific outcomes. This review demonstrates that integrating biosafety measures, chemical hygiene protocols, and green chemistry principles directly contributes to multiple Sustainable Development Goals, particularly those related to health, water quality, responsible consumption, and climate action. Moving forward, laboratories must adopt a holistic safety framework that combines regulatory compliance, continuous training, waste reduction strategies, and environmentally responsible research methods. Enhancing institutional safety culture and investing in sustainable laboratory infrastructure will enable scientific progress to advance in parallel with public health protection and environmental stewardship By synchronizing laboratory operational frameworks with internationally recognized sustainability objectives, research establishments can play an instrumental role in fostering the development of healthier human populations, ecologically resilient natural systems, and long-term environmental sustainability.

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