



e-ISSN No.: 2582-4228

# Journal of Indian Association for Environmental Management

Journal homepage: [www.http://op.niscair.res.in/index.php/JIAEM/index](http://op.niscair.res.in/index.php/JIAEM/index)



## Breaking the Cycle of Hazard: Protecting the Environment Through Sustainable Chemical Disposal

Fakeha Mohammed Rehan Shaikh<sup>1</sup> & Ashish Sambhaji Uzgare<sup>2\*</sup>

<sup>1</sup>Department of Chemistry, Faculty of Science, Wilson College (Autonomous), Mumbai-400007, Maharashtra, India.  
Corresponding Author: [ashish.uzgare@wilsoncollege.edu](mailto:ashish.uzgare@wilsoncollege.edu)

Submitted: 25 September 2025

Revised: 19 November 2025

Accepted: 23 November 2025

**Abstract:** Proper, safe, and eco-friendly disposal of chemical toxic waste is essential for protecting human health, conserving the environment, and promoting a more sustainable future. With the growth of industrialization and urbanization, the management of hazardous waste becomes progressively more complicated, demanding effective strategies to mitigate its harmful impact. The safe and responsible disposal of hazardous chemicals in research labs, academic institutions, industries and healthcare facilities is crucial to preventing risks to both public health and ecosystems. Proper disposal practices for substances like those used in electrophoresis and microbial waste are essential to avoid contamination and prevent the spread of pathogens and harmful materials. Similarly, the careful management and disposal of solvent chemicals in laboratories and biomedical waste in healthcare settings help mitigate long-term environmental and public health threats. It is also crucial to encourage collaboration among industries, governmental bodies, and waste management experts to ensure that best practices are followed globally, promoting consistency and effective waste management policies. This paper examines various safe disposal techniques, emphasizing the importance of minimization of toxic waste. It highlights the need for a comprehensive approach to toxic chemical disposal that minimizes pollution, protects ecosystems, and ensures long-term environmental well-being.

**Keywords:** Chemical toxic waste, Disposal techniques, Hazardous chemicals, Environmental impact.

### I. INTRODUCTION

Chemical toxic waste consists of materials that can cause death or harm to living organisms. These substances spread readily and can contaminate lakes and rivers. The term is often used interchangeably with "hazardous waste," which refers to discarded materials that pose long-term risks to both human health and the environment<sup>1</sup>. Scientists emphasize the need for effective waste treatment methods in educational institutions, agriculture, urban areas, and healthcare. These sectors generate small but highly dangerous quantities of chemical waste through both laboratory and non-laboratory activities<sup>2</sup>. Any material discarded without regard for its value is classified as waste. Incorrect handling, storage, transportation, disposal, or management of these wastes can pose serious risks to human health and the environment, including contamination of soil, air, and water. The disposal and management of hazardous waste pose significant challenges globally<sup>3</sup>. To minimize environmental pollution, it is crucial to reduce chemical waste, particularly in science teaching laboratories, in order to lessen both the environmental impact and disposal costs for universities. Several approaches can help reduce the waste

generated in these laboratories, including: eliminating or reducing pollution at its source, recycling and reusing chemicals, treating waste to reduce its hazards, adopting microscale chemistry techniques, and improving the management of chemical inventories within the laboratories<sup>4</sup>. Students learn to properly manage waste from research and classrooms, minimizing environmental harm. They also benefit from working in a safe, healthy, and clean environment that supports ecological principles<sup>5</sup>. The disposal of hazardous waste is the final step in a hazardous waste management system. Nearly all disposal methods require appropriate pre-treatment to ensure that the disposal facilities remain safe and secure<sup>6</sup>. Effective waste management strategies should align with circular economy models, focusing on economic, environmental, and efficiency goals<sup>7</sup>. Effective management of hazardous waste aligns with the principles of sustainable development. Sustainable development ensures that current needs are met without compromising the ability of future generations to meet their own needs, promoting a harmonious balance between human activities and environmental preservation<sup>8</sup>.

By addressing these areas, the review aims to provide a deep understanding of hazardous waste minimization and disposal methods.

### Safe disposal techniques for hazardous chemicals in research labs and institutions

The environmental impact of chemical waste from teaching and research is an escalating concern, prompting efforts to find solutions. Educational and research institutions generate small amounts of waste, much of it highly toxic, from both laboratory and non-laboratory activities. Some of this waste is identified by government agencies focused on environmental pollution, including acids, metals, solvents, chemicals, and the potentially unknown toxicity of certain synthetic byproducts<sup>9</sup>. Educational and research laboratories carry out experiments for training and research, using chemicals with various properties and characteristics. These laboratories typically involve a range of individuals, including academic staff, technicians, researchers, administrative personnel, students (undergraduate, master's, and PhD), and occasionally visitors. This diverse group makes effective waste management crucial for safeguarding human health. Poor chemical waste management is a commonly discussed issue due to its potential environmental and public health risks<sup>10</sup>. Chemicals used in laboratory activities pose risks to both the workplace and the environment, which need to be evaluated, managed, and mitigated. Creating a system to assess and rate the health, safety, and environmental risks associated with laboratory chemicals can help identify and understand potential hazards<sup>11</sup>. Fig 1 show Diagram of some common methods of disposal of hazardous chemical waste.

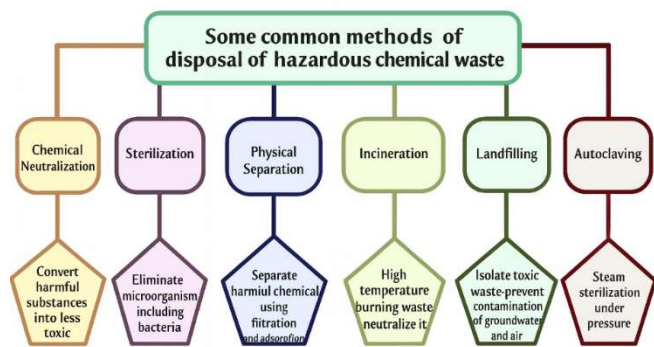


Fig 1. Diagram of some common methods of disposal of hazardous chemical waste

### Disposal Methods for Hazardous Chemicals Used in Electrophoresis

Electrophoresis is a widely used laboratory technique that applies electrical energy to separate molecules, such as proteins or nucleic acids, based on their size, structure, and electrical charge. This process presents potential safety hazards related to electricity, chemicals, and heat<sup>12</sup>. Electrophoresis waste that contains acrylamide or polyacrylamide must be treated as hazardous waste<sup>13</sup>. To ensure safe disposal and minimize hazardous waste, electrophoretic waste from DNA or protein identification must be handled in a way that protects public health and the environment. Mutagenic dyes like Ethidium

Bromide, Acridine Orange, SYBR Green I, SYBR Green II, SYBR Gold, and GelStar must be managed carefully, as they are known to be mutagenic. Gels containing these dyes, unused dye stock solutions, and contaminated debris must be disposed of through the Hazardous Waste Management Unit (HWMU). Gels that have been stained destained (with minimal dye remaining), and contain only trace amounts of dye in DNA/protein samples can be discarded in the trash. Contaminated non-sharp lab items (e.g., gloves, towels, tubes) should also be disposed of via the HWMU. Filtered buffer solutions, if free of dye (verified under UV light), can be safely disposed of down the drain with plenty of water, provided they do not contain other hazardous materials<sup>14</sup>. Fig 2 Shows Some methods of disposal of chemical in Electrophoresis.

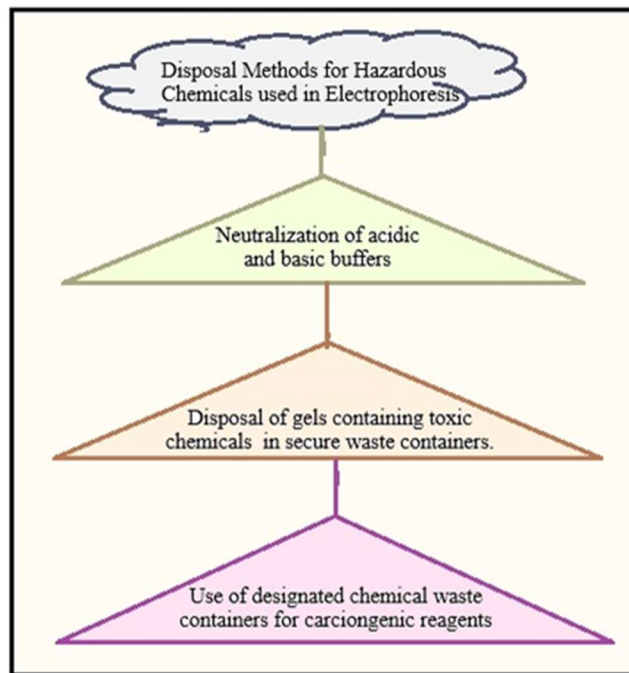


Fig 2. Some methods of disposal of chemical in Electrophoresis

### Methods for disposing of microbial waste

Microbiological waste, also known as biohazardous or biomedical waste, refers to materials contaminated or exposed to potentially infectious microorganisms, including viruses, bacteria, parasites, or fungi. This type of waste is commonly produced in healthcare and laboratory settings, research facilities, veterinary hospitals, and clinics during routine activities and procedures. Proper disposal methods for microbiological waste are essential to protect healthcare workers, scientists, staff, patients, visitors, and those handling the waste from exposure to harmful and dangerous contaminants<sup>15</sup>. Bacterial species identified in (full form) SMW from both healthcare facilities and households included *Bacillus subtilis*, *Klebsiella pneumonia*, *Pseudomonas aeruginosa*, *Clostridium tetani*, *Enterococcus faecalis*, *Acinetobacter spp.*, *Escherichia coli*, *Bacillus cereus*, and *Enterococcus faecium*. *Klebsiella pneumoniae*, *Acinetobacter spp.*, and *Clostridium tetani* were found only in untreated SMW from healthcare facilities. *Bacillus spp.* and *Pseudomonas spp.*

were detected in one sample of treated SMW. The microbial load in SMW from healthcare facilities ranged from  $0.036 \times 10^3$  cfu/mg to  $0.167 \times 10^3$  cfu/mg, while in households, it ranged from  $0.118 \times 10^3$  cfu/mg to  $0.125 \times 10^3$  cfu/mg. This emphasizes the need for improved treatment methods in sub-district healthcare facilities or better coordination with higher-level facilities to ensure proper treatment of SMW. Context-specific public guidance for the management of household-generated SMW should be provided<sup>16</sup>. Common waste management methods include chemical disinfection, steam sterilization, landfilling, and incineration<sup>17</sup>. Decontamination refers to processes that make medical devices, instruments or surfaces safe to handle. It includes sterilization, disinfection, and antisepsis. All infectious materials and contaminated equipment must be decontaminated before washing, storage, or disposal, with autoclaving being the preferred method. Decontamination methods include: Sterilization, A method to eliminate all microbial life, including resistant bacterial spores, Disinfection, Using chemicals to kill most pathogenic microorganisms, except bacterial spores, on surfaces and equipment. Effectiveness varies by organism type, exposure time, and conditions, Antisepsis, Applying antimicrobial chemicals to skin or living tissue to prevent or destroy microorganisms, such as during handwashing or prepping an injection site, Cleaning, Using water, detergent, and mechanical action to remove dirt and reduce microorganisms, often before sterilization or disinfection<sup>18</sup>. Autoclaving, which involves the use of saturated steam under pressure, is widely recommended and practiced for decontaminating infectious waste due to its reliability and ease of control on-site<sup>19</sup>. Rutala W A et al.<sup>20</sup> studied the effectiveness of autoclaving microbiological waste. They tested standardized loads of contaminated petri plates in polypropylene or stainless steel containers. The results showed that smaller loads and stainless steel containers improved heat transfer. A bag with rolled sides allowed better heat distribution than one with a twist-tie. The presence of water in the bag had little impact on heat-up time. To destroy *Bacillus stearothermophilus*, a 90-minute autoclave cycle in stainless steel containers was required. For 10 or 15 lb of waste, autoclaving for 45 minutes in stainless steel or polypropylene containers with water was effective, while 60 minutes was needed in polypropylene containers without water. Kollu, V. K. R et al.<sup>21</sup> conducted a study comparing two biomedical waste disinfection technologies: microwave (radiation-based) and autoclave (steam-based). The study evaluated their efficiency, efficacy, and cost-effectiveness. Both technologies achieved a similar level of disinfection, with nearly 100% reduction in microbial load. However, autoclaves required more time and resources, with operational costs over double those of microwaves. The study concluded that microwaves are a more cost-effective alternative for biomedical disinfection, with advantages including portability, tunability, and compactness. Pienpatanakij, N et al.<sup>22</sup> evaluated the effectiveness of autoclaving infectious biohazardous waste with and without the addition of water. Twelve bacterial and fungal strains were tested across three types of artificial waste. The results indicated that without water, some microorganisms, including *Bacillus cereus* and *Pseudomonas aeruginosa*, were not fully eradicated, and spore tests were still positive. However, when water was added to the waste bags, complete sterilization of all

microorganisms was achieved. These findings suggest that adding water improves sterilization efficiency and should be included as a standard practice in autoclaving procedures to prevent pathogen contamination.

### **Safe Methods for Disposing of biomedical waste from institutions and healthcare services**

Medical waste includes infectious, toxic, and hazardous materials produced by healthcare facilities during procedures like treatment, prevention, and healthcare services. This waste presents serious threats to human health and the environment. As such, its recycling and disposal must comply with stringent regulations and specific guidelines<sup>23</sup>. Medical waste encompasses infectious, toxic, or other hazardous materials (HMW). This type of waste is produced by medical institutions during medical or preventative care and associated activities, including infectious, pathological, pharmaceutical, and chemical waste<sup>24</sup>. Biomedical waste (BMW) can be in the form of solid or liquid waste and includes infectious or potentially infectious materials, such as medical, research, or laboratory waste. Improper management of BMW poses a significant risk of infections to healthcare workers, patients visiting the facilities, and the surrounding environment and community. BMW is also categorized into various types, including general, pathological, radioactive, chemical, infectious, sharps, pharmaceuticals, and pressurized waste. India has established comprehensive regulations for the proper handling and management of BMW<sup>25</sup>. Biological waste management technologies encompass methods such as composting, incineration, landfilling, anaerobic digestion, and bioconversion, which can be used to produce biofuels like bioethanol, biodiesel, and biogas<sup>26</sup>. Disposal methods such as terrestrial dumping, uncontrolled burning, and the improper disposal of hospital waste in landfills continue to be widely used, with many landfills operating in outdated and inefficient ways. Alternative treatment technologies for healthcare waste management, including incineration with heat recovery and waste gas cleaning, as well as accelerated composting, have been proposed. However, both of these methods face significant criticism<sup>27</sup>. In many regions, incinerating biomedical waste is the preferred method of disposal<sup>28</sup>. Incineration is an effective method for reducing waste volume, eliminating harmful microorganisms, and minimizing the uncontrolled disposal of heavy metals. The process generates a residual solid material known as biomedical waste ash (BMWA). By being repurposed in the construction industry, incinerated biomedical waste can help mitigate its environmental impact<sup>29</sup>. Incineration is a method that involves burning medical waste, and generating combustion gases and non-combustible residues (ash). The combustion gases are either released directly into the air or treated through air pollution control systems before being discharged. The non-combustible ash is collected from the incinerator and disposed of in landfills. The toxic ash residues in landfills pose a risk, as they can potentially contaminate groundwater through leaching<sup>30</sup>. Incinerated Biomedical Waste Ash (IBWA) remains toxic due to heavy metals and alkalinity, which can leach and harm the environment. Studies have revealed that IBWA can be used as a fine aggregate replacement in concrete, with bacterial treatment to reduce

alkalinity and heavy metal leaching. Concrete mixes were tested for strength, water absorption, chloride permeability, sulfate resistance, and TCLP over 365 days. *Bacillus Haloduran* was used to treat IBWA, lowering its toxicity. Various replacement levels (0%, 5%, 10%, 15%, 20%) of both untreated and bacterial-treated IBWA were evaluated for concrete performance<sup>31</sup>. Exposure to pollutants from incineration remains a significant public health issue. If incineration is considered a viable solution for healthcare waste, low-temperature incinerators should be banned and replaced with modern incinerators that have air pollution control systems. These challenges are common in developing countries that lack the resources to invest in environmentally protective incinerators with advanced technologies. As a result, alternatives like autoclaving and microwaving are viewed as better options for healthcare waste treatment<sup>32</sup>. Autoclaving is an effective wet thermal disinfection method commonly used in hospitals to sterilize reusable medical equipment. It is typically reserved for highly infectious waste, such as microbiological cultures and sharps, due to its capacity to process only small volumes of waste. Needles are autoclaved before being placed in the needle pit, and sharps from the needles are disposed of in puncture-resistant containers. All microbiological waste, including containers, plates, and tubes, undergo autoclaving before recycling or disposal. Due to the limitations of chemical treatments, blood banks are required to autoclave discarded or infected units prior to disposal<sup>33</sup>. Pathology, microbiology, blood banks, and diagnostic labs generate significant BMW, requiring audits for effective management. Sharps are autoclaved, and glass waste is disinfected before recycling. Formalin-fixed anatomical waste poses disposal challenges, and blood units need autoclaving before disposal. Liquid waste management requires more attention, and waste reduction, reuse, and recycling should be prioritized<sup>34</sup>.

### Minimize and Responsible Disposal of Harmful Solvent Chemicals from the Laboratory

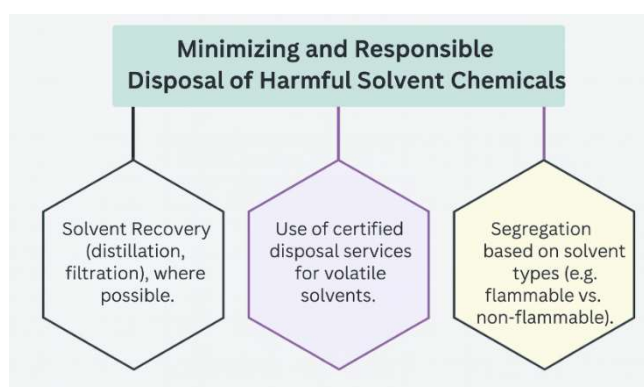


Fig 3. Diagram of Minimizing and Responsible Disposal of Harmful Solvent Chemicals

Fig 3 shows Diagram of Minimizing and Responsible Disposal of Harmful Solvent Chemicals. Green Universities and Education for Sustainable Development play a crucial role in building a sustainable society. As the need for sustainability becomes more urgent, universities are expected to equip students with the skills to integrate social, environmental, and economic factors in decision-making. Research institutions and

laboratories globally are also focused on implementing effective chemical waste management practices to reduce risks of accidents and minimize environmental and human contamination<sup>35</sup>. Every laboratory that uses chemicals generates waste, even if it's not immediately recognized as such. Cleaning agents, polishes, oils, mold inhibitors, and test samples are all examples of chemical waste found in non-chemical labs. Without clear instructions, waste disposal often happens by default, leading to inadequate handling. Therefore, some level of organization is necessary, even for minor labs. Regardless of the scale, however, waste disposal procedures should be as simple as possible and easy for staff to follow<sup>36</sup>. Educational and research institutions, through various laboratory and non-laboratory activities, produce small amounts of waste, many of which are highly toxic. Some of this waste is regulated by government agencies due to environmental concerns, including the disposal of acids, metals, solvents, and chemicals, as well as the toxicity of certain by-products of synthesis, the risks of which are often not fully known. Water-miscible substances like acetone can be safely flushed down the sink, but non-miscible liquids like toluene or carbon tetrachloride should never be disposed of this way. These substances can accumulate in the system, leading to dangerous blockages, corrosion, or even explosions years later. Water-insoluble materials dissolved in miscible solvents can precipitate when diluted, potentially clogging pipes. Since laboratory drains are often interconnected, chemicals from one sink can reappear as fumes in another. There is also a risk of chemicals from different sources mixing, such as sulphides and acids, which can result in hazardous reactions<sup>9,36</sup>. As water disposal became less acceptable, especially for handling new and more complex waste streams, the segregation and land burial of toxic substances became more commonly used methods<sup>37</sup>. Hazardous waste management involves transforming waste materials into less harmful or environmentally benign substances through biological, physical, chemical, and thermal processes. This is followed by the disposal or dispersal of solids, liquids, gases, or residues in a controlled manner<sup>38</sup>. To eliminate, reduce, or substitute hazardous chemicals, several strategies can be implemented. Hazardous chemicals should be eliminated whenever possible, such as replacing mercury thermometers and discontinuing the use of ethidium bromide in gels. Additionally, the development of solvent-free chemical reactions and the use of computer simulations can serve as alternatives to traditional experiments. When elimination is not feasible, the quantities of harmful chemicals, reagents, and precursors should be minimized. This can be achieved by opting for more efficient chemical reactions and utilizing green chemistry to replace toxic chemicals with less harmful alternatives<sup>39</sup>.

Safe disposal of hazardous chemicals and biomedical waste in chemical labs, research institute and healthcare settings is essential to protect human health and the environment. Implementing proper waste management practices minimizes risks and ensures sustainability.

## Effective Disposal Methods for Radioactive Waste Management

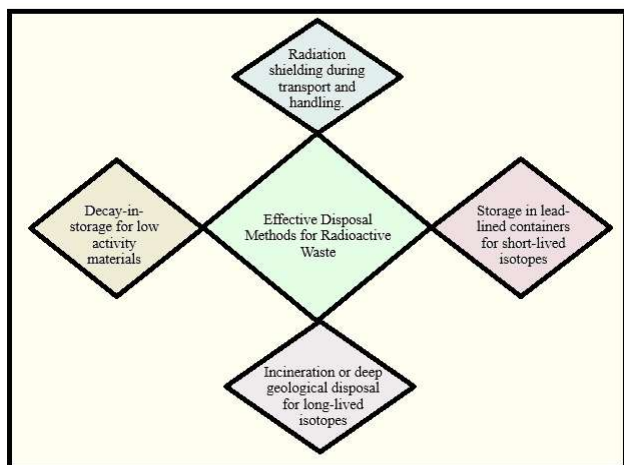


Fig 4. Some representation of disposal method of radioactive waste

Fig 4 Shows Some representation of disposal method of radioactive waste. Radioactive waste, generated by industries such as nuclear power, medicine, research, mining, and weapons reprocessing, contains radioactive materials or is contaminated by them and is deemed no longer useful. This waste poses significant risks to human health and the environment, requiring proper management to ensure exposure remains within regulated safety limits<sup>40</sup>. Nuclear power is crucial for providing scalable, affordable, and reliable low-carbon electricity, helping reduce reliance on fossil fuels, combat climate change, and promote sustainability. Despite progress in reducing radioactive waste volume, its management remains a key challenge as nuclear energy continues to expand. There have been latest technological and scientific advancements aimed at improving the safe, long-term management of nuclear power generation waste<sup>41</sup>. Ravichandran et al.<sup>42</sup> outlined the safe management of radioactive waste in hospitals, noting that while developed countries have well-organized systems, regions expanding nuclear medicine services need effective models. They introduced a waste storage trolley prototype to safely decay I-131 solid waste before it is released to the city's treatment plant. The study also described a two-tank system where effluents are stored for about two months before being released to the sewage treatment plant, ensuring that radioactive releases of I-131 remain below recommended levels. The results showed a good correlation between external sample measurements and calculated radioactive values, demonstrating the effectiveness of these disposal practices. Clayton R<sup>43</sup> discusses the role of nuclear power in achieving a sustainable, net-zero energy sector, emphasizing the need for attention to the back end of the nuclear fuel cycle specifically, the processing and disposal of radioactive waste. While various waste processing techniques are in use and novel technologies are being developed, prior research has mainly focused on technology and emissions, neglecting a life cycle perspective. This review reveals a lack of comprehensive life cycle assessments (LCAs) for radioactive waste management, with only a few relevant studies identified.

The research gap stems from insufficient data on waste treatment, conditioning, and disposal, making strategic analysis difficult. Future LCAs should focus on the back-end nuclear fuel cycle with greater detail to identify system "hotspots" and inform policy decisions, incorporating recent advancements in radiological impact assessments such as UCrAd.

Taş et al.<sup>44</sup> analyses the generation of radioactive waste, particularly in hospitals, where nuclear medicine uses radiopharmaceuticals for disease diagnosis and treatment. These wastes, resulting from the use of radiopharmaceuticals, require proper disposal methods. The disposal process for radiopharmaceutical waste differs from that of other radioactive wastes, as it is based on their specific classification. This classification depends on the physical and radiological characteristics of the radiopharmaceuticals.

Khan et al.<sup>45</sup> emphasize that tertiary care hospitals using radioisotopes for diagnostics and therapy must ensure safe radioactive waste disposal to prevent radiation exposure to individuals and the environment. According to the Atomic Energy (Safe Disposal of Radioactive Waste) Rules of 1987, hospitals must have the necessary infrastructure and trained staff to maintain radiation levels within safe limits. Regular monitoring of radiation levels in the hospital and among workers is required, with records kept on the type and amount of waste generated and its disposal method. The Radiation Safety Officer plays a crucial role in these operations. Grambow<sup>46</sup> outlines the research needs in radioactive waste management, highlighting important questions regarding historical trends and large-scale geological disposal projects. With varying industrial development across countries, this research is internationally oriented, long-term, and includes both fundamental and applied studies, with an emphasis on optimization. Lappi & Lintunen<sup>47</sup> examine the optimal operation of nuclear plants and waste management. They propose two rules: one for deciding when to continue electricity production and another for determining the ideal timing for nuclear waste disposal. These rules weigh the costs and benefits of ongoing production versus delaying disposal in a deep geological repository. The study also considers various regulatory approaches, including a shutdown tax, and suggests that a constant plant-specific fee could fund waste disposal. Their findings indicate that deep geological disposal is cost-effective only at very low interest rates; above 1%, long-term on-ground storage is more optimal.

Abdel Rahman & Ojovan<sup>48</sup> highlight that proper nuclear waste management starts with effective characterization, which involves determining the chemical, physical, biological, mechanical, and radiological properties of the waste. Radiological characterization presents challenges and requires a mix of traditional and innovative techniques. Their review explores the strategies for nuclear waste characterization, focusing on both nondestructive and destructive methods for analyzing waste packages. It also discusses separation methods for identifying important radionuclides, with an emphasis on radiometric techniques, and the use of scaling factor methodologies to ensure accurate characterization.

Holt et al.<sup>49</sup> explore processes to optimize radioactive waste before disposal, including thermal treatment for volume reduction, conditioning for homogenization, and immobilization for stabilization. They emphasize the importance of performance assessments to ensure the safety and durability of waste packages. The THERAMIN project demonstrated effective thermal techniques for reducing and immobilizing low- and intermediate-level waste, while the PREDIS project focused on treating metallic and organic waste and integrating digital solutions to improve safety and efficiency in waste handling and storage.

Effective radioactive waste management is crucial as nuclear energy expands, with advancements in treatment, storage, and characterization improving safety. Continued research is needed to address gaps in life cycle assessments and global standardization.

### **Managing Environmental pollutants in Chemical industries**

Since the Industrial Revolution, chemical pollutants have been emitted into the environment, with their release and spread significantly increasing over the past fifty years. Carbon dioxide emissions, which have long-term impacts on the climate, atmosphere, and oceans, serve as a prominent example. Numerous other substances have also been released through industrial and agricultural activities. Minimizing industrial pollution is a critical area of research aimed at reducing environmental harm and promoting sustainable industrial practices<sup>51</sup>.

Beschkov<sup>52</sup> discusses the environmental impact of chemical industries producing basic bulk chemicals. He emphasizes that preventing pollution is the most effective strategy for mitigating environmental harm. His paper covers traditional manufacturing processes, including sulfuric acid production, nitrate-based fertilizers, soda, caustics, cement, pharmaceuticals, and organic chemicals. It highlights how new technologies and processes that save raw materials, and energy, and promote by-product use and recycling contribute to both improved efficiency and environmental protection by reducing emissions to air, water, and soil. Masoumi, A., & Jalilzadeh Yengejeh, R.<sup>53</sup> discuss the expansion of oil production activities and the increased use of chemicals in the industry, leading to the generation of various waste types. Their study was conducted in accordance with international regulations such as the RCRA and Basel Convention. Although no established disposal method existed for these wastes, the findings indicated that over 73% of the chemical waste could be disposed of through sanitary landfilling. The case study examined more than 160 hazardous chemical substances. Lv, Y et al.<sup>54</sup> discuss the significant environmental challenges posed by salt waste in China's chemical production processes, where improper disposal methods, particularly landfilling, dominate. This practice exacerbates pollution and neglects the potential for recycling or reusing salt waste. The review highlights various valorization techniques, including oxidation, thermal treatment, washing separation, precipitation, and evaporation crystallization. It evaluates current technologies for resource recovery from salt waste and provides recommendations for

improving treatment and utilization, offering valuable insights for future waste management and resource recovery strategies. Kibria, M. G. et al.<sup>55</sup> analyze the generation of plastic waste, its effects on human health and ecology, and the sources in both developed and developing nations. It also reviews current waste-to-energy and product conversion methods, emphasizing sustainable management strategies and the challenges to minimizing the harmful effects of plastic waste. Singh, B. J.<sup>56</sup> presents a systematic literature review (SLR) on industrial wastewater management, analyzing challenges, enablers, and practices from the past decade. The study highlights the importance of regulatory frameworks, technological innovation, and sustainability, while addressing issues like inadequate infrastructure and resource constraints. Advanced technologies such as nanotechnology and bioremediation, along with circular economy principles, are identified as emerging areas. The research underscores the need for interdisciplinary collaboration and future exploration to enhance wastewater management. The study offers valuable insights for policymakers, researchers, and practitioners to tackle current challenges and opportunities. Shvetsova, O. A., & Lee, J. H.<sup>57</sup> explore the evaluation of waste treatment investment projects in South Korea and their impact on environmental policy development. The research offers insights into enhancing industrial waste management practices through effective investment strategies. Kumar, S. et al.<sup>58</sup> highlight India's major environmental challenges related to waste generation, inadequate collection, and disposal systems. With urbanization increasing waste volumes, current systems fail to protect the environment and public health. The paper emphasizes shifting from waste dumps to resource-recycling systems, including waste segregation and specialized processing facilities. It also discusses the potential for energy generation from landfill methane or thermal treatment, while noting the shortage of qualified professionals as a barrier to improved waste management.

Effective management strategies, such as waste segregation, recycling, and advanced treatment technologies, are essential for reducing pollution and promoting sustainability. Barriers like inadequate infrastructure, lack of qualified professionals, and reliance on traditional disposal methods hinder progress. Continued innovation, interdisciplinary collaboration, and investment in sustainable waste management systems are crucial for mitigating environmental harm and achieving long-term ecological balance.

### **Addressing the challenges of safe disposal methods**

Despite economic progress, effective waste management remains challenging, highlighting a gap in development strategies<sup>59</sup>. Rapid urbanization in developing countries in Asia and Africa has significantly increased municipal solid waste (MSW) generation. However, inadequate disposal strategies, limited land and financial resources, and unorganized public behavior have led to ineffective policy implementation and monitoring<sup>60</sup>. Waste contains various hazardous substances, unpleasant odors, and is difficult to manage, making it less attractive to businesses compared to other industries. Public support for waste management is often lacking at the

community level. In contrast, Waste-to-Energy (WtE) plants are typically profit-driven and often funded or controlled by the government. Problems arise when the responsibilities for WtE operations are split between different agencies, leading to interdepartmental conflicts that hamper plant efficiency. Many low-income countries face these issues. In Public-Private Partnerships (PPPs), contractors may focus more on financial gain than effective operations. A strong regulatory framework and coordinated planning team are needed to address these challenges and develop long-term strategies<sup>61</sup>. Fig 5 Shows Schematic diagram of addressing the challenges associated with safe disposal methods. As urbanization and economic growth accelerate, waste generation increases, putting significant strain on existing management systems.



Fig 5. Schematic diagram of addressing the challenges associated with safe disposal methods

## II. CONCLUSION

The safe and responsible disposal of toxic chemicals in research labs, institutions, and healthcare services is essential to protect both human health and the environment. Proper disposal methods for hazardous chemicals, such as those used in electrophoresis and microbial waste, are crucial to prevent contamination and the spread of harmful substances. However, despite the availability of various disposal techniques, a significant gap remains in terms of comparative data on their long-term environmental and health impacts, particularly in regions with limited resources and infrastructure. There is also a gap in the adoption of advanced, cost-effective technologies and in the implementation of standardized global guidelines, which creates inconsistencies in hazardous waste management practices.

Similarly, minimizing and responsibly disposing of harmful solvent chemicals in laboratories can prevent long-term environmental damage. Radioactive and biomedical waste from healthcare services must be disposed of using safe methods like incineration or specialized treatment to avoid risks to public health. Adopting proper disposal techniques and maintaining strict waste management protocols are key to fostering safe and sustainable practices in these critical sectors. In conclusion, addressing these existing gaps through multidisciplinary research, stronger policies, technological integration, and increased public awareness is essential for achieving a holistic and systematic approach to hazardous waste disposal that

ensures protection of both human health and the environment for future generations.

## Acknowledgment

The authors would like to acknowledge the contributions of the researchers listed in the references section, whose research publications were instrumental in the preparation of this review paper.

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