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A Review of Life Cycle Assessment of Nanomaterials-Based Adsorbent for Environmental Remediation

Bimastyaji Surya Ramadan[1], Yudha Gusti Wibowo[2,3], Dedy Anwar[3,4] and Anis Tatik Maryani[5]
[1]Department of Environmental Engineering, Universitas Diponegoro, Semarang, Indonesia.
[2]Sustainable Mining and Environmental Research Group, Department of Mining Engineering, Institut Teknologi Sumatera, Lampung-35365, Indonesia.
[3]Sustainable Mineral Processing Research Group, Department of Chemical Engineering, Universitas Gadjah Mada, Yogyakarya, Indonesia.
[4]Bioprocess Engineering Department, Institut Teknologi Del, Jalan Sisingamangaraja, Sitoluama, Laguboti, Toba, North Sumatera-22381, Indonesia.
[5]Postgraduate Program of Environmental Science, Universitas Jambi, Jambi-36122, Indonesia
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*to whom all correspondence should be addressed: e-mail: bimastyaji@live.undip.ac.id
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Graphical abstract

Abstract

Nanomaterials, known for their exceptional physicochemical properties, are used in electronics, skincare, catalysts, agriculture, and water treatment. Their small size and large surface area enable high adsorption capacities and rapid adsorption rates, effectively removing organic and inorganic pollutants from water. Designed as composites, nanomaterials enhance adsorption capacity, improve mechanical strength, and provide support matrices for retaining nanoparticles. Nanoadsorbents are particularly effective in removing toxic metals from wastewater and drinking water, targeting low concentrations of metals like arsenic, cadmium, lead, and mercury, crucial given stringent discharge regulations. However, the widespread use of nanomaterials poses potential health and environmental risks, as their production involves significant energy and material inputs, generating pollutants. Most research focuses on functionalities without considering life cycle environmental impacts. Life cycle assessment (LCA) is a comprehensive tool for evaluating these impacts, assessing products from cradle to grave, including raw material extraction, processing, manufacturing, distribution, use, maintenance, and disposal or recycling. LCA, based on the ISO 14040 series, includes four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation. This study categorizes existing research based on the four LCA phases, aiming to highlight current practices, challenges, and progress. The findings provide insights and recommendations for future research to ensure the sustainable development of nanomaterials.

Keywords: LCA; nanomaterials; environmental pollution; environmental remediation

1. Introduction

Nanomaterials exhibit exceptional physicochemical properties, making them valuable in various applications including electronics, skincare products, catalysts , agriculture , and water treatment (Saleem & Zaidi 2020a). Their small size and large surface area result in high adsorption capacities and rapid adsorption rates (Wibowo *et al.* 2022), enabling them to effectively remove organic and inorganic pollutants such as dyes and metals from contaminated water (Wibowo *et al.* 2023). Often designed as composites, nanomaterials incorporate additional components to enhance adsorption capacity, improve mechanical strength, or provide a support matrix to retain nanoparticles, thus facilitating their application and recovery (S. Wang *et al.* 2013; Wu *et al.* 2022). Nanoadsorbents are particularly effective in removing toxic metals from industrial wastewater or drinking water (El-sayed 2020), selectively targeting low concentrations of metals like arsenic, cadmium, lead (Mohan *et al.* 2007), and mercury (Budihardjo *et al.* 2021). This selective targeting is crucial as more stringent wastewater discharge regulations are being proposed, driving the development of nanomaterials with superior adsorption capabilities.

While nanomaterials offer numerous benefits across various sectors, their widespread use also raises potential health and environmental risks that are not yet fully understood. The production of Nanomaterials typically involves bottom-up processes such as physical and chemical vapor deposition, activation, carbonization, liquid-phase synthesis, and self-assembly, which require substantial energy and material inputs and generate pollutants in the form of effluents and emissions to air, water, and soil. To date, most research on Nanomaterials has concentrated on their unique functionalities in different applications without adequately considering the potential environmental impacts throughout their life cycle. There are also concerns about the environmental sustainability of NM production pathways and their contribution to environmental problems.

To address these concerns, a comprehensive tool like life cycle assessment (LCA) can be used to gain a better understanding of potential environmental issues and ensure the sustainability of Nanomaterials. LCA is a holistic approach that evaluates the environmental impacts of a product throughout its entire life cycle by identifying the materials used, energy consumed, and emissions released into the environment. This approach is crucial for assessing the potential impacts of nanomaterial releases. LCA is an internationally standardized methodology, based on the ISO 14040 series, comprising four phases: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment, and (iv) life cycle interpretation. Developed to assess the environmental impact of products and their associated processes, LCA provides a robust framework for evaluating the sustainability of nanomaterials.

The rapid advancement of nanotechnology necessitates a closer examination of the environmental toxicity pathways associated with nanomaterials through the lens of LCA. However, existing studies in this field often lack consistency in methodological approaches, data collection methods, and characterization techniques, leading to inconclusive or contradictory results. Consequently, there is a need to explore the current state of LCA application in nanotechnology to understand prevailing practices and future prospects. In this study, content analysis is employed to categorize existing research based on the four phases of LCA. This approach aims to shed light on the current practices, challenges, and progress in LCA application to nanomaterials. It is essential to highlight these aspects to provide insights and recommendations for future studies in this crucial area.

2. Life Cycle Assessment (LCA) Framework:

The concept of LCA is a critical tool in environmental management, encapsulating the full evaluation of the environmental impacts associated with all the stages of a product's life from cradle to grave—from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. This comprehensive method provides a detailed look at the environmental impacts of products and services, making it indispensable for sustainable design and production.

LCA is defined as a systematic process that evaluates the environmental aspects and potential impacts associated with a product, process, or service (Jacquemin *et al.* 2012). By considering the entire lifecycle, LCA provides a complete picture of the environmental impacts and helps identify opportunities for improvement that would not be apparent when looking at only one stage of the product life. LCA helps to understand the full range of environmental impacts from the extraction of raw materials to the disposal of end products. Figure 1 provides an overview of the importance of evaluating the environmental impact of nanomaterials and categorizes existing studies based on the four phases of LCA.

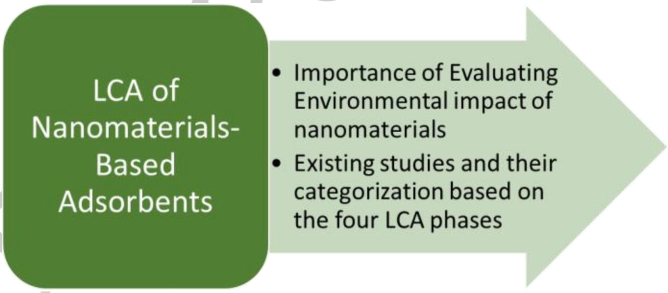

Figure 1. Overview of the importance and categorization of Life Cycle Assessment (LCA) of Nanomaterials-Based Adsorbents.

The scope of an LCA can vary widely but typically includes energy and water use (Mannan & Al-Ghamdi 2020), emissions to air (X. Zhang *et al.* 2013), water (Vince *et al.* 2008), soil (Garrigues *et al.* 2012), resource depletion (Klinglmair *et al.* 2014), and waste generation (Hossain & Poon 2018). This tool is extensively used in policy making, industrial processes, and product design to reduce environmental footprints, make comparisons between options, and inform decision-makers.

The methodology of LCA is structured around four main phases as outlined in ISO 14040:2006:

1. Goal and Scope Definition: This initial phase involves defining the purpose of the study, the system boundaries, and the level of detail required. It sets the framework for the assessment.
2. Inventory Analysis (LCI): This phase involves data collection and calculation procedures to quantify relevant inputs and outputs of a system. It forms the basis of the LCA and involves compiling and quantifying inputs and outputs for a product throughout its life cycle.
3. Impact Assessment (LCIA): This stage aims to evaluate the magnitude and significance of the potential environmental impacts using the LCI data. It involves selecting appropriate impact categories, such as global warming potential, ozone layer depletion, eutrophication, and acidification.

4. Interpretation: The final phase involves evaluating the results from the LCIA to make informed decisions that can help mitigate environmental impact. It includes identifying significant issues based on the results of the inventory analysis and impact assessment phases.

An LCA study breaks down the lifecycle into distinct stages that each contribute to the overall environmental footprint of the product:

1. Raw Material Acquisition: This stage involves the extraction and processing of raw materials from the earth, which is often energy-intensive and can lead to significant environmental degradation.
2. Production: The manufacturing process typically consumes resources and energy, and generates waste and emissions. This stage looks at the transformation of raw materials into finished products.
3. Utilization: This stage covers the use of the product by the end-user, including energy and resource needs during operation or consumption. It also considers maintenance and potential reuse during the product's lifetime.
4. Disposal: The final stage includes end-of-life processes such as recycling, incineration, or landfill. It evaluates the impacts of disposal methods and the potential for resource recovery.

LCA helps in making informed choices by highlighting which stages of a product's life cycle are the most environmentally significant. This is crucial for targeting interventions that can significantly reduce environmental impacts. For example, if the production stage is found to be the most impactful, efforts can focus on adopting cleaner production techniques, improving energy efficiency, or shifting to renewable energy sources.

2.1. Environmental Indicators

Environmental indicators in LCA are quantitative measures that help assess the environmental impacts associated with all stages of a product's life cycle—from the extraction of raw materials through manufacturing, use, and disposal. These indicators are crucial for identifying significant environmental impacts and for making informed decisions to minimize negative effects (García-García *et al.* 2021). This section elaborates on key environmental indicators such as carbon footprint, energy consumption, and resource depletion, and discusses the importance of quantifying and analyzing these indicators in LCA studies.

2.1.1. Explanation of Key Environmental Indicators

1. **Carbon Footprint:** The carbon footprint is a widely recognized environmental indicator that measures the total greenhouse gas emissions caused directly and indirectly by an individual, organization, event, or product, expressed as carbon dioxide equivalent (CO2e). In the context of LCA, it includes the emissions throughout the product's life cycle, encompassing CO2 emissions during raw material extraction, production, transportation, usage, and disposal phases (Aßen *et al.* 2014).
2. **Energy Consumption:** Energy consumption measures the amount of energy used in the life cycle of a product. It encompasses all forms of energy (e.g., electrical, mechanical, thermal) required during the extraction of raw materials, manufacturing processes, transportation, product use, and end-of-life stages. This indicator is crucial for assessing the efficiency of resource use and for identifying opportunities to improve energy efficiency and switch to renewable energy sources (Klinglmair *et al.* 2013).
3. **Resource Depletion:** This indicator focuses on the consumption of natural resources, such as minerals, water, and fossil fuels, throughout a product's life cycle. Resource depletion is critical for understanding the sustainability of resource use, especially in terms of the availability of non-renewable resources and the impact of their extraction and consumption on the environment (Peters & Weil 2016).

2.1.2. Importance of Quantifying and Analyzing These Indicators in LCA Studies

- Identifying **Key Impact Areas:** Quantifying environmental indicators helps identify which stages of a product's life cycle are most impactful from an environmental perspective. This information is vital for targeting interventions that can significantly reduce environmental impacts, such as optimizing resource use or improving energy efficiency.
- **Informing Decision-Making:** Detailed analysis of environmental indicators enables companies, policymakers, and consumers to make informed decisions. For manufacturers, it might inform choices about materials or production methods. For consumers, it could guide purchasing decisions towards more sustainable options.
- **Benchmarking and Improvement:** By quantifying these indicators, organizations can benchmark their products against industry standards or competitors. This benchmarking can serve as a foundation for setting improvement goals, tracking progress over time, and communicating environmental performance both internally and externally.
- **Regulatory Compliance and Reporting:** Many regions and sectors are increasingly subject to environmental regulations that require reporting on specific environmental indicators. LCA provides a standardized method to calculate these indicators, ensuring compliance and helping in the formulation of regulatory strategies.
- **Enhancing Corporate Sustainability:** Quantifying environmental impacts through LCA helps companies enhance their sustainability practices by providing a clear picture of their environmental footprint. This transparency is crucial not only for internal management but also for corporate reporting, which can influence investor relations and public perceptions.

In summary, environmental indicators like carbon footprint, energy consumption, and resource depletion play pivotal roles in LCA studies by quantifying and elucidating the environmental impacts associated with different life cycle stages of products. These indicators are indispensable for fostering environmental sustainability, guiding strategic decisions in business and policy, and enhancing the ecological responsibility of products throughout their life cycle.

3. Assessment of Raw Materials

The selection of raw materials in the lifecycle assessment of products holds pivotal importance as it significantly influences the environmental and economic sustainability of the entire process. When companies choose raw materials, they consider several crucial factors, each of which plays a role in determining the feasibility and impact of the end product.

One primary consideration is the availability of the raw material. Materials need to be sufficiently available to ensure steady production without supply chain disruptions. The geographical source of these materials also impacts the selection process, as sourcing materials from stable and accessible regions minimizes transportation impacts and potential geopolitical risks. Moreover, the cost of raw materials often dictates their selection. While companies aim for cost-effective solutions to maintain profitability, this economic consideration must be balanced with environmental and social costs, which are increasingly prioritized in global production standards (Achzet & Helbig 2013; Eğilmez *et al.* 2017). Figure 2 illustrates the key environmental impacts assessed in the extraction process and transportation impact of raw materials.

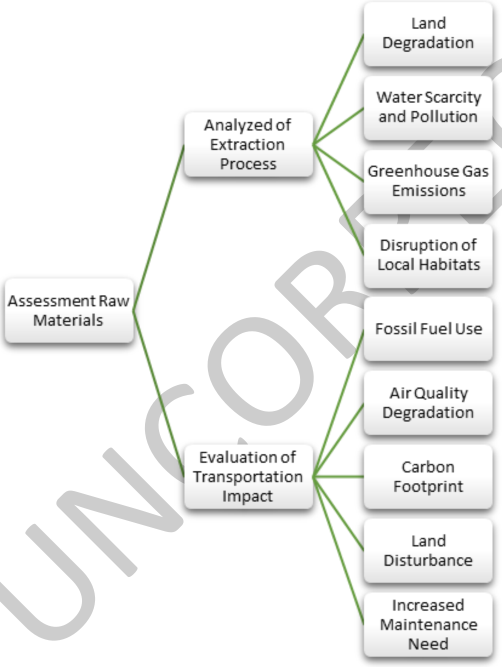

Figure 2. Life Cycle Assessment (LCA) of raw materials, focusing on the analyzed extraction process and transportation impact.

The technical performance and quality of raw materials are also critical. Materials must meet specific technical requirements pertinent to the product's functionality, including durability and strength. These characteristics ensure that the product performs as expected over its intended lifespan without premature breakdowns or failures, which could negatively impact consumer trust and brand reputation. Additionally, all materials used must comply with stringent regulatory and compliance requirements, which vary from one region to another and may include restrictions on hazardous substances, safety standards, and environmental impact limits (Chu *et al.* 2020; Giannakopoulou *et al.* 2021).

Consumer preferences and market demands are increasingly guiding the selection of raw materials. There is a growing trend toward sustainable and ethically sourced products as consumers become more environmentally conscious. This shift in consumer behavior is prompting companies to choose raw materials that are not only environmentally friendly but also socially responsible, thus aligning product offerings with consumer expectations for sustainability (Benotsmane *et al.* 2021).

When it comes to considerations for sustainability and environmental impact, the extraction and processing of raw materials come under scrutiny. The extraction processes, often involving mining and quarrying, have significant impacts on local ecosystems, including habitat destruction, soil erosion, and pollution. Similarly, the processing of raw materials can be energy-intensive and polluting, depending on the methods used. Therefore, selecting materials that require less energy-intensive processes or that generate fewer emissions during extraction and processing can substantially reduce the overall environmental footprint of the products (Settembre-Blundo *et al.* 2018; Terrones-Saeta *et al.* 2021).

Renewability and recyclability of raw materials are increasingly becoming a part of sustainable material selection strategies. Renewable materials, such as bamboo, wood from sustainably managed forests, and bioplastics derived from biological sources, are preferred over finite resources like minerals and fossil-based plastics. These renewable materials are often more favorable in terms of environmental impact, as they can be replenished over time and help reduce waste and depletion of natural resources (Hospodárová *et al.* 2018).

Moreover, the life cycle potential of a material, including its ability to be recycled or reused, plays a critical role in its selection. Materials that can be easily recycled or repurposed at the end of the product's life help promote a circular economy, where waste is minimized, and materials are kept in use for as long as possible. This approach not only reduces the demand for virgin raw materials but also decreases waste and environmental pollution (Miemczyk *et al.* 2012).

Social responsibility is another critical factor in the selection of raw materials. This involves considering the social impacts associated with material extraction, including labor conditions, community impacts, and indigenous rights. Ethically sourced materials that support fair labor practices and contribute to the economic development of local communities are increasingly valued. Companies are recognizing that sustainable sourcing practices not only help mitigate risks but also enhance brand reputation and customer loyalty (Zorzini *et al.* 2015).

In addition to these factors, technological advancements and innovations in material science often lead to the development of new materials that meet the increasing demands for sustainability and performance. These advancements can offer alternatives to traditional materials that are less harmful to the environment and are more energy-efficient to produce (Miller 2013).

The integration of environmental, economic, and social considerations into the raw material selection process is essential for achieving sustainability in product development. By carefully assessing the source, cost, impact, and lifecycle potential of raw materials, companies can make informed decisions that benefit not only their bottom line but also the environment and society at large (Dewulf *et al.* 2015). As global awareness and regulations concerning sustainability continue to evolve, the criteria for selecting raw materials are likely to become even more stringent, pushing companies towards more innovative and environmentally responsible manufacturing practices (O'Rourke 2014). This holistic approach to raw material selection is a critical component of modern environmental management strategies, aiming to align industrial practices with global sustainability goals (Dewulf *et al.* 2015).

3.1. Environmental Impacts of Raw Material Acquisition

The acquisition of raw materials, a critical initial stage in the lifecycle of any product, brings with it significant environmental impacts that can affect ecosystems, contribute to pollution, and lead to resource depletion. Understanding these impacts is crucial for developing strategies that mitigate environmental damage and promote sustainability in product manufacturing (Finnveden *et al.* 2009; Haapala *et al.* 2013; Ruben *et al.* 2019; W. Zhang *et al.* 2019).

3.1.1. Analysis of Extraction Processes

The extraction of raw materials often involves intensive processes such as mining, drilling, and harvesting from the natural environment. These processes are resource-intensive and can have profound environmental impacts, including land degradation, water scarcity, and pollution. Mining operations, for example, strip the land, leaving it vulnerable to erosion, while the process itself can result in substantial water and air pollution from the chemicals used to extract minerals. Similarly, the drilling for oil or gas can lead to oil spills and leakage of harmful chemicals into the groundwater and surrounding soil (Joshi 1999).

The environmental costs of these extraction processes are considerable. They not only deplete natural resources but also disrupt local habitats and biodiversity. The machinery used in these operations often emits large amounts of carbon dioxide and other greenhouse gases, contributing to the broader issue of climate change (Settembre-Blundo *et al.* 2018). Moreover, the alteration of landscapes and the removal of vegetation cover can lead to habitat loss for many species, pushing local wildlife out of their natural habitats and disrupting ecological balance (Zhuang *et al.* 2019).

3.1.2. Evaluation of Transportation Impacts

Once raw materials are extracted, they must be transported to manufacturing sites, which can be located great distances away. The transportation of raw materials involves trucks, ships, and trains, all of which consume fossil fuels and emit carbon dioxide and other pollutants into the atmosphere. The impact of these emissions includes contributing to global warming, deteriorating air quality, and acid rain, which can harm forests, soils, water bodies, and the organisms that live in these environments (Zhong *et al.* 2019).

Moreover, the transportation infrastructure itself can also lead to environmental degradation. The construction and maintenance of roads, railways, and ports often involve further land disturbance, habitat destruction, and pollution (J. Zhang *et al.* 2021). Heavy vehicles used in the transportation of heavy materials can also cause significant wear and tear on roads, leading to increased maintenance needs and associated environmental impacts from the construction activities required for these repairs (J. Zhang *et al.* 2021; Zulfikri 2023).

3.1.3. Assessment of Potential Ecosystem Disturbances

The cumulative effects of raw material extraction and transportation can lead to significant ecosystem disturbances. Ecosystems are dynamic and complex; even small changes in the environment can ripple through the system, leading to unexpected consequences (Neary *et al.* 2009). For instance, the removal of trees for timber not only reduces the forest cover but also affects the soil's ability to retain water, leading to increased runoff and erosion. This can alter river courses and affect water quality downstream, impacting aquatic life and the availability of clean water for human and agricultural use (Bhattacharyya *et al.* 2015; Wilhelm *et al.* 2017).

Additionally, the noise and human activity associated with extraction processes can disrupt the natural behavior of wildlife. Animals may be forced to migrate, which can lead to overpopulation in certain areas and underpopulation in others, disrupting local biodiversity. Furthermore, when ecosystems are disturbed or destroyed, carbon stored in trees and soil is released into the atmosphere, contributing to increased atmospheric CO2 levels and thus global warming (Maxwell *et al.* 2006).

The environmental impacts of raw material acquisition highlight the need for industries to adopt more sustainable practices. This includes using technologies that minimize environmental disruption, recycling materials to reduce the need for new raw materials, and choosing extraction sites and methods that lessen environmental impacts. Regulations and policies can also drive improvements by setting standards for sustainable extraction and encouraging or requiring companies to restore environments after extraction activities are completed (Abdul-Rashid *et al.* 2017).

4. Production Processes

The synthesis of nanomaterials-based adsorbents is a rapidly evolving area of research due to their high efficiency and potential applications in environmental remediation, such as water purification and air filtration. The production of these nanomaterials involves various synthesis methods, each with specific energy and resource requirements. Understanding these methods and their implications is crucial for optimizing production processes and minimizing environmental impacts (Gan *et al.* 2020; Subramaniam *et al.* 2019).

Nanomaterials, with their unique properties and vast potential applications, have garnered significant attention in various fields, including environmental remediation, biomedical sciences, electronics, and energy production. Among the diverse range of applications, the synthesis of nanomaterials-based adsorbents stands out as a crucial area, particularly in the context of pollution control and environmental sustainability (Istrati *et al.* 2021).

Various synthesis methods have been developed and refined to fabricate nanomaterials-based adsorbents, each offering distinct advantages and limitations in terms of energy consumption, resource utilization, efficiency, and environmental impact. Figure 3 illustrates the different synthesis methods and their associated environmental impacts.

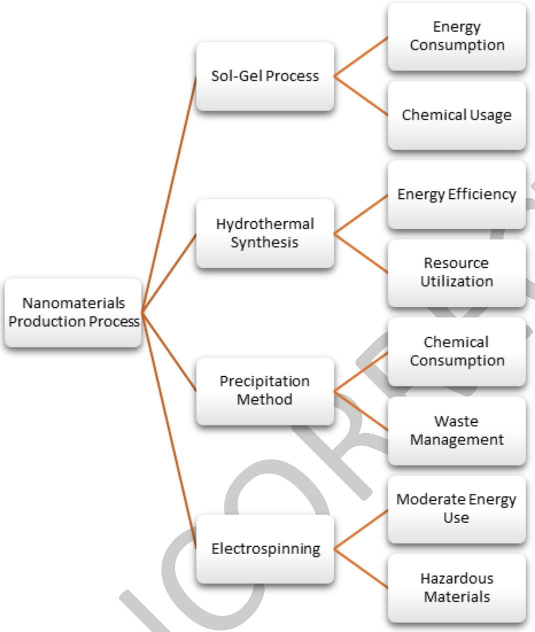

Figure 3. Nanomaterials production processes, highlighting the different synthesis methods and their respective environmental impacts.

One prominent synthesis method is the sol-gel process, which involves the conversion of a chemical solution (sol) into a gel phase through chemical reactions and subsequent drying . While the sol-gel process enables precise control over the composition, structure, and morphology of the resulting materials, it typically requires significant amounts of energy for solvent evaporation and gel drying. This energy-intensive aspect often involves heating the system to temperatures ranging from 500 to 600°C (Hench & West 1990). Furthermore, the chemical precursors used in the sol-gel process, such as metal alkoxides, tend to be expensive and may pose toxicity risks, necessitating careful handling and disposal measures to minimize environmental and health hazards (Jiao *et al.* 2023; Rodríguez-Alonso *et al.* 2022).

Another widely employed synthesis technique is hydrothermal synthesis, which involves the reaction of precursor materials in an aqueous solution at elevated temperatures and pressures within a sealed autoclave (Li *et al.* 2017). Despite being energy-intensive due to the high temperatures and pressures required to maintain the autoclave environment, hydrothermal synthesis offers advantages in resource efficiency (Ndlwana *et al.* 2021). By utilizing water as the solvent and sometimes allowing the use of less pure feedstocks, it reduces the demand for refined chemicals compared to other synthesis methods. This resource-efficient characteristic contributes to the sustainability of the hydrothermal synthesis process (Li *et al.* 2017; Subramaniam *et al.* 2019).

The precipitation method is another approach commonly used for synthesizing nanomaterials-based adsorbents. In this method, the desired material is precipitated from a solution by the addition of a precipitating agent or by adjusting the pH of the solution (Tamez *et al.* 2016). While the precipitation method is generally less energy-intensive than sol-gel and hydrothermal synthesis, it can lead to high chemical consumption, particularly when adjusting pH or employing large quantities of precipitating agents. The generation of waste during the precipitation process poses environmental challenges, necessitating proper treatment before disposal to prevent contamination and minimize environmental impact (Hajjaoui *et al.* 2021; Tamez *et al.* 2016).

Electrospinning represents a unique synthesis technique for producing nanomaterials-based adsorbents, particularly those composed of polymeric materials. In electrospinning, a high voltage is applied to a polymer solution or melt, resulting in the formation of ultrafine fibers through the stretching and solidification of the polymer jet. While electrospinning consumes moderate amounts of energy, primarily for maintaining the high voltages required and facilitating solvent evaporation, it offers advantages in terms of tunable morphology and porosity of the resulting materials. However, the polymers and solvents used in electrospinning can be hazardous, requiring adequate ventilation and recycling procedures to minimize exposure and environmental impact (Balakrishnan *et al.* 2020; Tan & Rodrigue 2019).

Despite their differences, all these synthesis methods play critical roles in the development of nanomaterials-based adsorbents for various applications, particularly in pollution control and environmental remediation. As the demand for effective adsorbents continues to grow, driven by increasing environmental pollution and sustainability concerns, there is a pressing need to enhance the efficiency and sustainability of these synthesis techniques (Lv *et al.* 2018; Tan & Rodrigue 2019).

Ongoing research efforts aim to address the challenges associated with energy consumption, resource utilization, and environmental impact in nanomaterials synthesis.

Strategies such as process optimization, alternative precursor materials, and the development of novel synthesis approaches are being explored to improve the sustainability of nanomaterials synthesis for adsorbent applications (C. Liu *et al.* 2010).

One promising direction in the advancement of synthesis methods is the development of green synthesis approaches that minimize energy consumption, reduce the use of hazardous chemicals, and promote the use of renewable resources. Green synthesis techniques, such as microwave-assisted synthesis, sonochemical synthesis, and biosynthesis using biological organisms or plant extracts, offer potential advantages in terms of energy efficiency, resource utilization, and environmental sustainability (Singh *et al.* 2018).

Microwave-assisted synthesis utilizes microwave irradiation to facilitate rapid heating of reaction mixtures, leading to shorter reaction times, reduced energy consumption, and improved overall efficiency compared to conventional heating methods (G. Yang & Park 2019). Sonochemical synthesis involves the use of high-intensity ultrasound waves to induce chemical reactions in solution, offering advantages such as rapid reaction kinetics, precise control over reaction conditions, and reduced energy consumption (Gedanken 2004).

Biosynthesis approaches harness the metabolic activities of biological organisms or the bioactive components of plant extracts to produce nanomaterials under mild reaction conditions. These green synthesis methods offer inherent advantages in terms of sustainability, biocompatibility, and the avoidance of hazardous chemicals, making them attractive options for the fabrication of nanomaterials-based adsorbents for environmental applications (Dhillon *et al.* 2011).

In addition to green synthesis approaches, efforts are underway to develop novel synthesis strategies that combine the advantages of different methods while mitigating their respective limitations. For example, hybrid synthesis approaches that integrate aspects of sol-gel, hydrothermal, and precipitation methods offer the potential to tailor the properties of nanomaterials-based adsorbents more effectively while minimizing energy consumption and resource utilization (Subramaniam *et al.* 2019).

Furthermore, advancements in nanomaterials synthesis are closely linked to developments in characterization techniques and computational modeling, which enable a deeper understanding of the structure-property relationships governing the performance of adsorbent materials. By leveraging techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), and computational modeling, researchers can gain insights into the morphology, crystallinity, surface chemistry, and adsorption properties of nanomaterials, guiding the rational design and optimization of synthesis strategies (Sebastián *et al.* 2013).

In conclusion, the synthesis of nanomaterials-based adsorbents for pollution control and environmental remediation presents both challenges and opportunities in terms of energy consumption, resource utilization, and environmental sustainability. While existing synthesis methods such as sol-gel, hydrothermal, precipitation, and electrospinning offer valuable capabilities, there is a need for continued research and innovation to enhance their efficiency and sustainability.

Green synthesis approaches, including microwave-assisted synthesis, sonochemical synthesis, and biosynthesis, hold promise for reducing energy consumption, minimizing environmental impact, and promoting the sustainable production of nanomaterials-based adsorbents. Additionally, the development of hybrid synthesis strategies and advancements in characterization techniques and computational modeling are key drivers for the future advancement of nanomaterials synthesis for environmental applications.

By addressing these challenges and capitalizing on emerging opportunities, researchers can contribute to the development of sustainable nanomaterials synthesis methods that support the effective management of environmental pollution and contribute to a more sustainable future.

4.1. Environmental Impacts of Production

The environmental impacts of producing nanomaterials-based adsorbents are multifaceted, encompassing energy consumption, water usage, emissions, and overall environmental footprints. To understand these impacts comprehensively, it is crucial to delve into the quantification of each factor, evaluate their interdependencies, and compare the environmental footprints of different synthesis routes. This analysis not only highlights the sustainability challenges but also sheds light on potential pathways for improvement (Pallas *et al.* 2018).

Energy consumption is a critical factor in the environmental assessment of nanomaterials synthesis. The sol-gel process, for instance, is known for its high energy demand. The necessity to heat the system to temperatures as high as 500-600°C for solvent evaporation and gel drying significantly contributes to its energy footprint. Such high-temperature processes require substantial energy inputs, typically derived from fossil fuels, leading to considerable greenhouse gas emissions. This high energy consumption translates directly into a larger carbon footprint, making the sol-gel process less favorable from an environmental perspective (Kim & Fthenakis 2012).

Hydrothermal synthesis, on the other hand, also requires high temperatures and pressures to maintain the autoclave environment. While it is similarly energy-intensive, hydrothermal synthesis can sometimes be more resource-efficient. The use of water as the solvent and the potential to utilize less pure feedstocks reduce the need for highly refined chemicals, which themselves require energy-intensive processes for purification. This aspect of hydrothermal synthesis can mitigate its overall energy footprint compared to methods relying heavily on refined chemicals. However, the continuous energy input to maintain high-pressure and high-temperature conditions still poses significant environmental challenges (Fu & Wang 2011; Woo 2023).

The precipitation method offers a different set of considerations. While generally less energy-intensive than both sol-gel and hydrothermal synthesis, it can lead to high chemical consumption. The adjustment of pH levels and the use of large quantities of precipitating agents generate substantial chemical waste. This waste not only represents an inefficient use of resources but also poses disposal challenges. Proper treatment of this waste is essential to prevent environmental contamination, requiring additional energy and resources. Consequently, while the direct energy consumption may be lower, the overall environmental impact remains significant due to the high chemical usage and associated waste management requirements (Fu & Wang 2011; Ren *et al.* 2012).

Electrospinning is another method that presents unique energy and environmental challenges. This process requires moderate energy levels, primarily for maintaining high voltages necessary for the formation of nanofibers and for solvent evaporation systems (Capello *et al.* 2007). The polymers and solvents used in electrospinning can be hazardous, necessitating stringent ventilation and recycling procedures to mitigate health risks and environmental contamination. The moderate energy consumption combined with the potential hazards of the materials used underscores the need for careful environmental management in electrospinning operations (Christé *et al.* 2020). Table 1 provides a comparison of energy consumption, water usage, and emissions across different nanomaterial synthesis methods.

Table 1. Comparison of Energy Consumption, Water Usage, and Emissions across Different Nanomaterial Synthesis Methods

Synthesis Method	Energy Consumption	Water Usage	Emissions
Sol-Gel	High	Low	High
Hydrothermal	High	High	Moderate
Precipitation	Low to Moderate	Moderate	Moderate to High
Electrospinning	Moderate	Low	Moderate

Beyond energy consumption, water usage and emissions are critical components of the environmental assessment. Hydrothermal synthesis, due to its reliance on water as a solvent, involves significant water usage (Ndlwana *et al.* 2021). While water is a more environmentally benign solvent compared to organic solvents, the large volumes required can strain local water resources, especially in water-scarce regions. Additionally, the wastewater generated from hydrothermal processes contains various reaction byproducts, necessitating effective treatment before discharge to avoid environmental pollution (Shi *et al.* 2013).

Emissions from nanomaterials synthesis processes can include greenhouse gases, volatile organic compounds (VOCs), and other air pollutants. The sol-gel process, with its high-temperature requirements, often leads to significant CO2 emissions. Similarly, the use of organic solvents in electrospinning can release VOCs, contributing to air quality degradation and posing health risks to workers. Quantifying these emissions involves monitoring air quality parameters and using emission factors to estimate the environmental impact of each synthesis route (Eckelman *et al.* 2012; Nowack *et al.* 2011).

Comparing the environmental footprints of different synthesis routes requires a comprehensive evaluation of their cumulative impacts. Life cycle assessment (LCA) is a valuable tool in this regard, providing a holistic view of environmental performance from raw material extraction through production and end-of-life disposal. LCA considers factors such as resource depletion, energy consumption, greenhouse gas emissions, and water usage, enabling a detailed comparison of the environmental footprints of different synthesis methods (Gavankar *et al.* 2012; Nowack *et al.* 2011; Pallas *et al.* 2018).

Through LCA, it becomes evident that while each synthesis method has its unique advantages and limitations, there are overarching themes in their environmental impacts. For instance, energy-intensive processes like sol-gel and hydrothermal synthesis, while effective in producing high-quality nanomaterials, tend to have larger carbon footprints due to their substantial energy requirements. On the other hand, methods like the precipitation process, though less energy-demanding, can generate significant chemical waste, complicating their environmental sustainability.

The pursuit of greener synthesis approaches is essential to address these challenges. Green synthesis methods, such as microwave-assisted synthesis, sonochemical synthesis, and biosynthesis, hold promise for reducing energy consumption and minimizing environmental impact. Microwave-assisted synthesis leverages microwave irradiation to achieve rapid heating, reducing reaction times and energy consumption compared to conventional heating methods. Sonochemical synthesis uses high-intensity ultrasound waves to induce chemical reactions, offering advantages such as rapid kinetics and precise control over reaction conditions, with lower energy inputs (Singh *et al.* 2018).

Biosynthesis, which utilizes biological organisms or plant extracts, offers an inherently sustainable approach by operating under mild reaction conditions and avoiding hazardous chemicals. These green synthesis techniques represent significant steps toward more sustainable production methods, aligning with the broader goals of environmental protection and resource conservation.

5. Utilization Phase

The utilization phase of nanomaterials-based adsorbents for environmental remediation is critical in understanding their overall life cycle impacts. Life Cycle Assessment (LCA) provides a comprehensive framework to evaluate these impacts from cradle to grave, including the production, utilization, and disposal stages. Focusing on the utilization phase, LCA examines the effectiveness, efficiency, and environmental impacts of nanomaterials-based adsorbents when deployed for environmental remediation purposes (Khin *et al.* 2012; Sadegh *et al.* 2017; S. Zhang *et al.* 2022).

Nanomaterials-based adsorbents are increasingly used for removing pollutants from air, water, and soil due to their high surface area, tunable surface properties, and exceptional adsorption capacities. Their effectiveness in capturing contaminants such as heavy metals, organic pollutants, and toxic gases plays a significant role in their life cycle assessment. These adsorbents demonstrate high adsorption efficiency, often achieving rapid pollutant removal compared to conventional materials. The selectivity of these adsorbents allows for targeted removal of specific contaminants, thereby enhancing the overall efficacy of the remediation process. For example, activated carbon nanotubes can selectively adsorb heavy metals like lead and cadmium from water, while graphene oxide composites effectively remove organic pollutants like phenols and dyes (Bao *et al.* 2018; Khin *et al.* 2012; Saleem & Zaidi 2020b).

The ability to regenerate and reuse nanomaterials-based adsorbents significantly impacts their environmental footprint. Efficient regeneration techniques, such as thermal treatment, chemical washing, or electrochemical methods, enable multiple cycles of use, reducing the need for frequent replacement and thereby lowering the overall environmental burden (Dichiara *et al.* 2014). Reusability extends the functional life of the adsorbents and minimizes waste generation, contributing positively to their life cycle sustainability (Omorogie *et al.* 2014).

While the utilization phase emphasizes the functional benefits of nanomaterials-based adsorbents, it is also essential to consider the environmental impacts associated with their use in remediation processes. The operational energy required for deploying nanomaterials-based adsorbents can vary depending on the remediation technology. For instance, using nanomaterials in fixed-bed adsorption systems, fluidized beds, or continuous flow systems involves different energy inputs for pumping, mixing, and maintaining optimal conditions (Creamer & Gao 2016). The energy efficiency of these systems directly influences the environmental performance of the adsorbents during the utilization phase.

Some nanomaterials-based adsorbents may require chemical activation or modification to enhance their adsorption properties. The use of chemicals during the utilization phase, such as for regeneration or surface functionalization, can introduce additional environmental burdens. Proper management of chemical waste and ensuring safe disposal practices are crucial to mitigate potential environmental contamination. A significant concern in the utilization phase is the potential leaching and release of nanomaterials into the environment. The stability of nanomaterials-based adsorbents under various environmental conditions determines their risk of leaching. If nanomaterials detach from the adsorbents and enter natural ecosystems, they may pose ecotoxicological risks to aquatic and terrestrial organisms. Therefore, evaluating the leaching behavior and developing strategies to minimize the release of nanomaterials are critical components of their life cycle assessment (Gottschalk *et al.* 2009).

The comparative analysis of the environmental footprint of nanomaterials-based adsorbents versus conventional adsorbents provides insights into their relative sustainability. This comparison involves several key factors. Nanomaterials typically offer higher material efficiency due to their large surface area and enhanced adsorption capacity. This efficiency translates to lower material usage for achieving the same level of pollutant removal compared to conventional adsorbents like activated carbon or zeolites (Saleem & Zaidi 2020b; Walkey & Chan 2012). The durability and longevity of nanomaterials-based adsorbents affect their environmental footprint. Materials with longer operational lifespans reduce the frequency of replacement and associated environmental impacts from production and disposal (G. Yang & Park 2019). In contrast, conventional adsorbents may require more frequent replacement, leading to higher cumulative impacts over the same period. The disposal phase of nanomaterials-based adsorbents is a critical consideration in their life cycle assessment. Safe disposal methods, such as encapsulation, stabilization, or incineration, need to be evaluated to prevent environmental contamination (Peydayesh & Mezzenga 2021). The potential for recycling or repurposing spent nanomaterials adsorbents can further enhance their environmental sustainability (Walkey & Chan 2012).

Several strategies can be employed to enhance the sustainability of nanomaterials-based adsorbents during the utilization phase. Developing green synthesis methods for nanomaterials that minimize the use of hazardous chemicals and reduce energy consumption can significantly lower their environmental impact. Additionally, surface modification techniques that employ environmentally benign reagents can enhance the adsorption properties without introducing additional environmental burdens. Utilizing renewable energy sources, such as solar or wind power, to drive the adsorption and regeneration processes can reduce the carbon footprint of nanomaterials-based adsorbents. Integration with renewable energy technologies can make the overall remediation process more sustainable and cost-effective. Improving regeneration techniques to enhance the efficiency and effectiveness of adsorbent recovery can extend their operational lifespan and reduce waste generation. Innovations in thermal, chemical, and electrochemical regeneration methods can contribute to more sustainable utilization of nanomaterials-based adsorbents. Continuous monitoring and assessment of the lifecycle impacts of nanomaterials-based adsorbents are essential for identifying areas for improvement and implementing corrective measures. Incorporating real-time data collection and analysis into lifecycle assessment frameworks can provide actionable insights for optimizing environmental performance (J. Yang *et al.* 2019).

The utilization phase of nanomaterials-based adsorbents for environmental remediation is a critical determinant of their overall lifecycle sustainability. By evaluating their effectiveness, efficiency, and environmental impacts through comprehensive life cycle assessments (Wolfbeis 2015), it is possible to identify key areas for improvement and develop strategies to enhance their sustainability. Focusing on green synthesis, renewable energy integration, advanced regeneration techniques, and continuous lifecycle monitoring can significantly contribute to the sustainable deployment of nanomaterials-based adsorbents in environmental remediation efforts. This holistic approach not only supports pollution control and environmental protection but also advances the broader goals of sustainable development and resource conservation.

5.1. Environmental Implications of Adsorption

The environmental implications of adsorption, particularly when using nanomaterials-based adsorbents, encompass a range of concerns from the potential release of nanomaterials into the environment to the fate of adsorbed contaminants. These implications must be carefully evaluated to ensure that the benefits of using such advanced materials do not inadvertently lead to new environmental problems (Gottschalk *et al.* 2009; Haq *et al.* 2021; Radnik *et al.* 2021; C. Sun *et al.* 2022; Wigger *et al.* 2020). Figure 4 illustrates the key aspects of potential release of nanomaterials and the fate of adsorbed contaminants during the utilization phase.

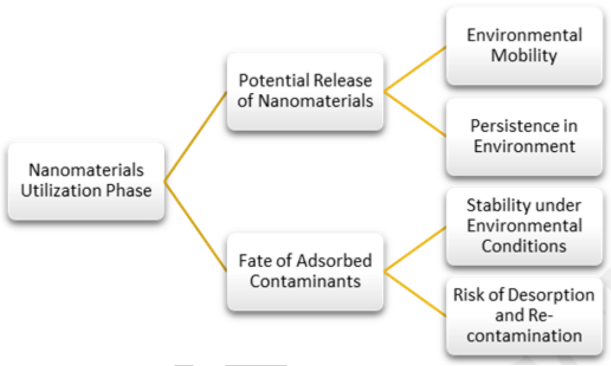

Figure 4. Life Cycle Assessment (LCA) of the utilization phase of nanomaterials, highlighting the potential release of nanomaterials and the fate of adsorbed contaminants.

One significant environmental concern associated with nanomaterials-based adsorbents is the potential for their release into the environment during and after their use. Nanomaterials, by their very nature, are designed to be highly reactive and possess unique properties that enhance their adsorption capacities. However, these same properties can make them more mobile and persistent in the environment if they are released unintentionally (Gottschalk *et al.* 2009; T. Y. Sun *et al.* 2016; Thakur & Kumar 2023).

The stability of nanomaterials in different environmental conditions is a critical factor. For instance, the high surface area and reactivity that make nanomaterials effective adsorbents can also make them more prone to leaching under certain conditions. Factors such as pH, temperature, and the presence of other chemicals can influence the stability and potential release of nanomaterials from the adsorbents. If these materials detach from the adsorbents and enter natural ecosystems, they can pose ecotoxicological risks to both aquatic and terrestrial organisms (Capsoni *et al.* 2022; Fadeel *et al.* 2015; Ghadimi *et al.* 2020). The impact on microbial communities in soil and water, for instance, can disrupt essential ecological functions, potentially leading to broader environmental consequences (Gambardella & Pinsino 2022; Zubair 2024).

To mitigate these risks, it is essential to develop and implement strategies that enhance the stability of nanomaterials-based adsorbents and prevent their release. This might include modifying the surface of nanomaterials to reduce their mobility, using encapsulation techniques, or designing composite materials that bind the nanomaterials more securely (Q. Sun *et al.* 2017).

Another critical aspect to consider is the fate of the contaminants adsorbed by nanomaterials-based adsorbents. While these materials are effective at capturing and removing pollutants from various media, the ultimate disposition of these adsorbed contaminants must be managed carefully to prevent secondary pollution (Yin *et al.* 2019).

Once contaminants are adsorbed onto nanomaterials, their stability on the adsorbent surface and the potential for desorption under changing environmental conditions become key concerns. For instance, changes in pH or ionic strength in the environment where the adsorbents are deployed can trigger the release of previously adsorbed contaminants, potentially leading to re-contamination of the environment. This phenomenon is particularly relevant in dynamic environments such as rivers or coastal areas where such parameters can fluctuate significantly (Yin *et al.* 2019).

Additionally, the methods used for regenerating nanomaterials-based adsorbents can influence the fate of adsorbed contaminants. Thermal regeneration, chemical washing, or electrochemical methods used to restore the adsorbent's capacity might release the contaminants back into the environment if not properly managed. Therefore, developing closed-loop regeneration processes that safely contain and treat the desorbed contaminants is crucial (Homaeigohar 2020).

Several case studies highlight the environmental impacts of using nanomaterials-based adsorbents during the utilization phase. These examples illustrate both the potential benefits and challenges associated with their application.

One notable example is the use of graphene oxide-based adsorbents for removing heavy metals from wastewater. Graphene oxide's high surface area and functional groups make it highly effective at adsorbing metals like lead, cadmium, and mercury. However, studies have shown that under certain environmental conditions, graphene oxide can degrade and release both the adsorbed metals and graphene fragments into the environment. This underscores the importance of understanding the long-term stability and environmental behavior of these materials (Madadrang *et al.* 2012; Velusamy *et al.* 2021).

In another case, titanium dioxide nanoparticles have been used for the photocatalytic degradation of organic pollutants in water. While highly effective at breaking down contaminants under UV light, concerns have been raised about the potential for titanium dioxide nanoparticles to persist in the environment and cause harm to aquatic life. Research has shown that these nanoparticles can accumulate in organisms, leading to potential bioaccumulation and biomagnification issues (Fukugaichi 2019; Mohan & Pittman 2007).

A further example involves the use of iron oxide nanoparticles for the remediation of arsenic-contaminated groundwater. Iron oxide nanoparticles have a strong affinity for arsenic, effectively reducing its concentration in water. However, the disposal of arsenic-laden nanoparticles poses a significant challenge. If not properly contained, these nanoparticles can release arsenic back into the environment, posing a risk to both human health and ecosystems (Mohammadian *et al.* 2022; Saif *et al.* 2019).

6. End-of-Life Management

End-of-life management is a critical aspect of the life cycle of nanomaterials-based adsorbents, particularly when it comes to their disposal. Proper disposal methods are essential to prevent environmental contamination and to ensure that the benefits of using these advanced materials do not lead to unintended ecological harm. The primary disposal methods for nanomaterials-based adsorbents include landfilling, incineration, and recycling. Each method has distinct environmental impacts that must be carefully analyzed. Figure 5 illustrates the key environmental impacts and challenges associated with different disposal methods, including landfilling, incineration, and recycling.

6.1. Overview of Disposal Methods

Landfilling involves the burial of waste materials in designated landfill sites. This method is commonly used due to its relative simplicity and low cost. However, the stability of nanomaterials in landfill conditions and their potential to leach into soil and groundwater pose significant environmental concerns (Gottschalk *et al.* 2009).

Incineration entails burning waste materials at high temperatures. This method can effectively reduce the volume of waste and potentially destroy hazardous contaminants. However, the process can also generate harmful emissions, including nanoparticles, which need to be carefully managed to avoid air pollution (Teodoro *et al.* 2021).

Recycling aims to recover and reuse valuable materials from waste. For nanomaterials-based adsorbents, this might involve processes to regenerate the adsorbents for reuse or to reclaim valuable nanomaterials. Recycling can significantly reduce the environmental footprint by minimizing waste and reducing the need for virgin materials (Hochella *et al.* 2019; Nam 2024; Pati *et al.* 2016).

6.2. Analysis of Environmental Impacts

Landfilling: The environmental impacts of landfilling nanomaterials-based adsorbents primarily revolve around leaching and long-term stability. Nanomaterials, due to their high reactivity and small size, can migrate from the landfill into surrounding soil and groundwater. This migration can lead to contamination of water resources and soil, posing risks to both human health and the environment. Furthermore, the presence of adsorbed contaminants on the nanomaterials can exacerbate these risks. While liners and leachate collection systems in modern landfills are designed to mitigate such issues, the long-term effectiveness of these measures remains a concern (Vaverková *et al.* 2018).

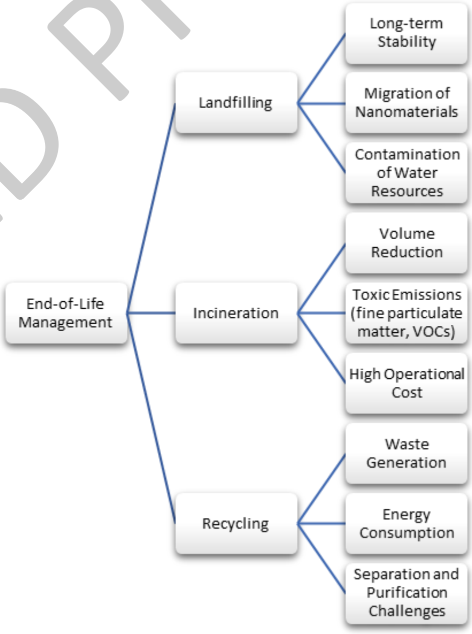

Figure 5. End-of-Life Management of nanomaterials, highlighting the environmental impacts and challenges associated with landfilling, incineration, and recycling.

Incineration: The incineration of nanomaterials-based adsorbents can effectively reduce waste volume and neutralize certain hazardous contaminants. However, the high temperatures required for incineration can lead to the release of nanoparticles and other toxic emissions into the atmosphere. These emissions, including fine particulate matter and volatile organic compounds (VOCs), can contribute to air pollution and pose respiratory health risks. Advanced incineration technologies with stringent emission controls, such as high-efficiency particulate air (HEPA) filters and scrubbers, can mitigate some of these impacts but may significantly increase the operational costs (Vejerano *et al.* 2013).

Recycling: Recycling nanomaterials-based adsorbents offers several environmental benefits, including reduced waste generation and conservation of resources. By regenerating the adsorbents or reclaiming valuable nanomaterials, recycling minimizes the need for new raw materials and reduces the environmental burden associated with their extraction and processing. However, the recycling process itself can present challenges. The regeneration of adsorbents often requires chemical or thermal treatments that consume energy and may produce secondary waste. Additionally, the separation and purification of nanomaterials from complex waste streams can be technically challenging and costly. Ensuring the economic viability and environmental sustainability of recycling processes is crucial for their widespread adoption (Y. Liu *et al.* 2014).

6.3. Comparative Analysis

When comparing these disposal methods, it is clear that each has its strengths and weaknesses. Landfilling is the simplest and most cost-effective option but poses significant long-term environmental risks. Incineration effectively reduces waste volume and destroys some contaminants but can lead to harmful emissions that require careful management. Recycling offers substantial environmental benefits by conserving resources and reducing waste but faces technical and economic challenges that need to be addressed (Saleem & Zaidi 2020b).

A comprehensive approach to the end-of-life management of nanomaterials-based adsorbents should prioritize the most sustainable methods. This includes improving the stability of nanomaterials to prevent leaching in landfills, enhancing emission controls in incineration processes, and developing more efficient and cost-effective recycling technologies. By adopting a combination of these strategies, it is possible to minimize the environmental impacts of nanomaterials-based adsorbents at the end of their life cycle and ensure their continued contribution to environmental remediation efforts.

6.4. Recycling and Circular Economy

Recycling and Circular Economy are pivotal components in addressing the contemporary challenges posed by resource depletion and environmental degradation. Within this framework, the potential for material recovery and recycling stands as a beacon of hope, offering a sustainable pathway towards preserving finite resources and mitigating ecological harm (Perathoner 2014). As societies grapple with the ramifications of unsustainable consumption patterns, exploring strategies to achieve circularity in adsorbent disposal emerges as a pressing imperative, underscoring the necessity for innovative approaches and collaborative efforts across various sectors (Troschinetz & Mihelcic 2009).

At the heart of the discourse lies the recognition of the finite nature of resources and the urgent need to transition towards more sustainable practices. Material recovery and recycling present promising avenues for mitigating the adverse impacts of resource depletion by extending the lifespan of materials and reducing the demand for virgin resources (Perathoner 2014). By reclaiming and reprocessing materials at the end of their lifecycle, recycling not only conserves valuable resources but also minimizes energy consumption and greenhouse gas emissions associated with conventional extraction and production processes. Thus, fostering a robust recycling infrastructure is essential in harnessing the full potential of material recovery to build a more sustainable future (Troschinetz & Mihelcic 2009).

However, realizing the full potential of recycling necessitates a multifaceted approach that addresses various challenges and barriers impeding its efficacy (Troschinetz & Mihelcic 2009). One such challenge lies in the complexity of waste streams, characterized by diverse materials and contaminants that pose significant hurdles to efficient recycling processes (Z. Wang *et al.* 2011). To overcome this challenge, innovative sorting technologies and advanced recycling techniques are indispensable, enabling the separation and purification of materials with higher precision and efficiency (Troschinetz & Mihelcic 2009). Moreover, fostering public awareness and participation is crucial in promoting recycling behavior and facilitating the segregation of waste at the source, thereby enhancing the quality and quantity of recyclable materials available for recovery (Z. Wang *et al.* 2011).

Furthermore, achieving circularity in adsorbent disposal presents a unique set of challenges and opportunities within the broader context of the circular economy. Adsorbents play a critical role in various industrial processes and environmental remediation efforts, serving to capture and remove contaminants from air, water, and soil. However, the disposal of spent adsorbents poses environmental risks and resource inefficiencies, underscoring the need for sustainable management strategies that prioritize material recovery and reuse (Geissdoerfer *et al.* 2017).

One strategy for achieving circularity in adsorbent disposal revolves around the concept of closed-loop systems, wherein spent adsorbents are collected, regenerated, and reintegrated into the production cycle. By implementing efficient regeneration processes, such as thermal desorption or chemical regeneration, spent adsorbents can be rejuvenated, thereby extending their lifespan and reducing the demand for virgin materials. Moreover, integrating renewable energy sources and green technologies into regeneration processes can further enhance the sustainability of closed-loop systems, minimizing environmental impacts and resource consumption (Savaskan *et al.* 2004).

In addition to closed-loop systems, exploring alternative uses for spent adsorbents presents another avenue for achieving circularity and maximizing resource utilization. For instance, spent adsorbents enriched with certain metals or minerals can be repurposed for secondary applications, such as construction materials or catalysts, thereby creating value from waste and reducing the burden on natural resources. Furthermore, leveraging advancements in material science and nanotechnology can unlock new possibilities for the upcycling of spent adsorbents into high-value products with enhanced functionalities and performance characteristics (GadelHak *et al.* 2022).

However, realizing the full potential of circularity in adsorbent disposal requires concerted efforts from stakeholders across the value chain, including government agencies, industry players, and research institutions. Policy interventions, such as extended producer responsibility (EPR) schemes and mandatory recycling targets, can incentivize businesses to adopt more sustainable practices and invest in innovative recycling technologies. Moreover, fostering collaboration and knowledge-sharing platforms can facilitate the exchange of best practices and foster innovation in the field of adsorbent disposal, driving continuous improvement and adaptation to evolving challenges (Schumacher & Green 2022).

7. Conclusion

The utilization phase of nanomaterials-based adsorbents is crucial for understanding their overall environmental impact. These adsorbents are highly effective in removing pollutants from air, water, and soil due to their high surface area and exceptional adsorption capabilities. They can efficiently capture contaminants like heavy metals and organic pollutants, making them valuable tools in environmental remediation. Nanomaterials-based adsorbents can often be regenerated and reused, reducing the need for frequent replacements and lowering their environmental impact. However, the energy and chemicals required for regeneration can introduce additional environmental burdens, which must be managed to ensure sustainable use.One major concern is the potential release of nanomaterials into the environment during use. If they detach from the adsorbents, they could pose risks to ecosystems. Therefore, developing methods to minimize this risk is essential. Compared to conventional adsorbents like activated carbon, nanomaterials typically offer higher efficiency and longer lifespans, which can reduce overall environmental impact. However, safe disposal methods and potential for recycling are critical considerations.To enhance the sustainability of these adsorbents, developing green synthesis methods, using renewable energy for processes, and improving regeneration techniques are key strategies. Continuous lifecycle assessment and monitoring can help optimize their environmental performance and support broader sustainability goals.

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