IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)
e-ISSN: 2319-2402, p- ISSN: 2319-2399.Volume 19, Issue 4 Ser. 1 (April 2025), PP 46-55
www.iosrjournals.org

Reconciliation of Sustaining Environmental Impact of Nanomaterials: An Overview

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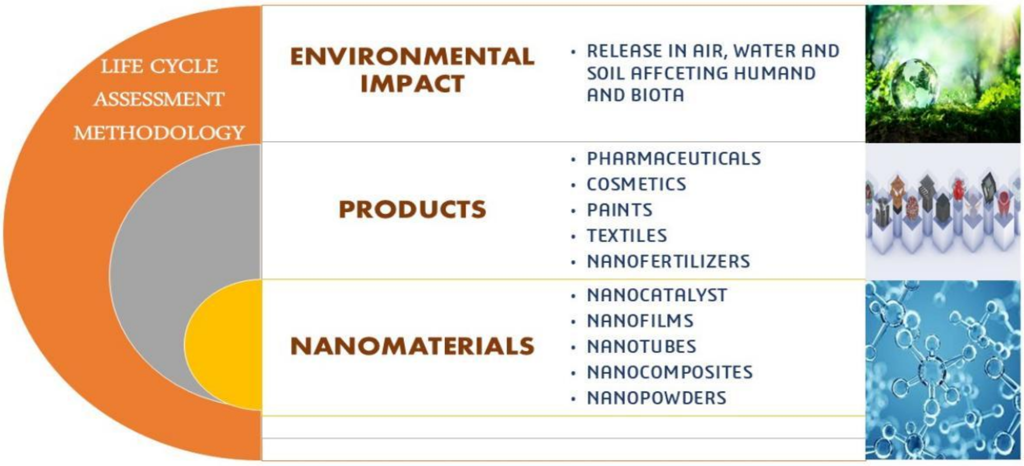
Abstract
Authors have attempted to explore the reconciliation of sustaining the environmental impact of nanomaterials. Certain pulsating contemplations lead towards the exhausting production, the latent discharge of nanoparticles into the environment, resulting into respective perseverance. However, there is demand of certain revolutionary solutions in reference to nanomaterials linked bioremediation, relevant unimpeded proliferation may perhaps overstress environmental deterioration, ultimately resulting into probability of hazards to living systems including human. As a consequence of achieving sustainability in nanomaterials, there is well obvious demand of a multifaceted approach for reconciliation of sustaining ecological impact of nanomaterials. Further, these coordinated studies together emulate amalgamating ecological contemplations into the strategy followed by synthesis procedure, engaging green engineering approaches, then executing vigorous principles to lessen potential threats. This review article delivers novel perceptions into establishing strong platform including principled exposure of the extensive potential of nano-substances though protecting environmental veracity intended for forthcoming cohorts.
Keywords: *Environmental veracity, Ecological impact, Green engineering, Nano-substances, Sustainability.*

Date of Submission: 18-04-2025 Date of Acceptance: 28-04-2025

Graphical Abstract



I. Introduction

The seriousness to discourse demanding environmental issues has never been more evident in this promptly changing world. Our planet faces unparalleled challenges, from pollution and climate change to resource depletion, demanding pioneering solutions because these pollutants can enter the food chain, posing health risks and environmental apprehension [1-5]. The risk of nanomaterials (NMs) is strengthened by factors like their environmental concentrations, linked contaminants, transformations, consumption, bioaccumulation, and ecotoxicity [3-5]. Nanotechnology and nanomaterials are often employed in evolving technologies pointed at environmental sustainability and addressing these existing challenges. The exceptional possessions of nanomaterials, such as high surface-to-volume ratios, increased reactivity, and quantum effects, make them remarkably valuable for endeavouring a wide range of issues. Therefore, nanotechnology has the potential to meaningfully contribute to attaining sustainable progress goals and nurturing a sustainable society.

1. Environmental Impacts and Apprehensions

The environmental impact of nanomaterials is a growing apprehension because of their exclusive features and extensive applications.

1.1. Toxicity and Bioaccumulation:

There is growing apprehension about the toxicity and exposure of nanomaterials (NMs), as they can infiltrate and be absorbed by the cell membranes of mammals. The rate at which NMs are absorbed by cells depends solely on their size, aggregation, and sedimentation properties. The small size of nanoparticles permits them to permeate the physiological barriers of living organisms, leading to injurious biological reactions. Nanoparticles can pass in the human body through the lungs, intestinal tract, or skin, and they can possibly be toxic to the brain, result in lung inflammation, and induce cardiac problems [6]. Due to their size and conformation, certain nanoparticles have been discovered to induce permanent cell damage by triggering organ injury and oxidative stress [Figure 1; 7-10].

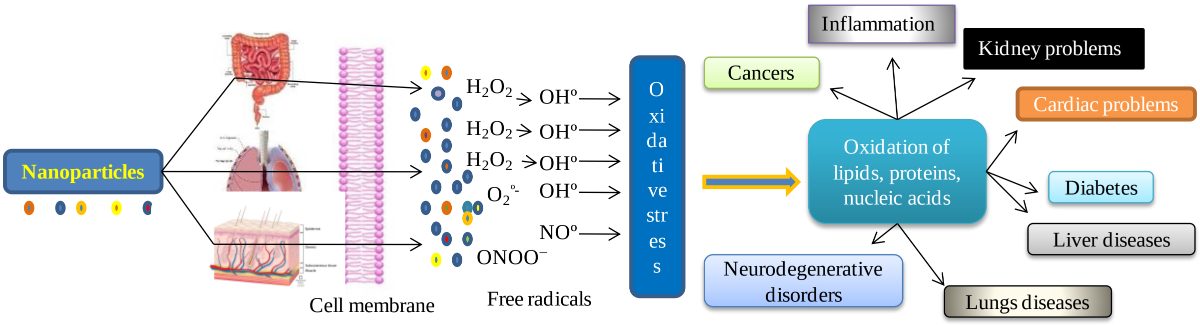


Figure 1. Nanoparticles versus oxidative stress and potential harmful effects

Several studies conducted by Sahu et al. highlight that size is the most critical factor in the genotoxicity and cytotoxicity of silver nanomaterials (Ag NMs) on human liver cells. These studies found that the toxic effects of Ag NMs varied according to their size, with smaller NMs having a more potent impact [11]. Likewise, gold nanomaterials (Au NMs) are widely considered in several medical applications but are famed to affect human embryonic stem cells, primarily depending on their size. Stem cells exposed to 1.5 nm gold NMs showed decreased cohesiveness and detachment, pointing to cellular death, while larger NMs at 4 nm and 14 nm showed no signs of toxicity [12]. In addition to size, nanomaterials (NMs) shape can importantly influence their effects on human health. Fibroblast cells showed higher toxicity to gold nanospheres approximately 61.5 nm in size compared to nanostars with a smaller diameter of about 33.7 nm [13].

Research on the phytotoxicity of nanoparticles has exposed both beneficial and detrimental effects on higher plants. TiO_2 nanoparticles have been reported to heighten photosynthesis and nitrogen metabolism, thus advancing the growth of spinach at optimal concentrations. In contrast, alumina nanoparticles have been noticed to have no adverse effects on the growth of *Phaseolus vulgaris* and *Lolium perenne* [14]. Nevertheless, these nanoparticles were registered to suppress root elongation in *Zea mays, Cucumis sativus, Glycine max, Brassica oleracea, and Daucus carota* [15]. Moreover, high concentrations of nano-sized ferrophase particles have been observed to inhibit the growth of popcorn [16]. In spite of these findings, the mechanism behind phytotoxicity remnants unclear, and there is limited information on the uptake of nanoparticles by plants and their fate within food chains. The internalization and upward movement of ZnO nanoparticles ~~has~~ have been successfully examined in *Lolium perenne* [17]. Employing light, scanning electron, and transmission electron microscopy, they observed root uptake and phytotoxic effects. Their results disclosed that exposure to ZnO nanoparticles significantly reduced *Lolium perenne* biomass, caused root tips to shrink, and resulted in highly vacuolated or collapsed root cortical and epidermal cells. Although, the translocation of Zn from root to shoot was marginal under ZnO nanoparticle treatments.

The aggregation process of nanoparticles is highly affected by many factors, including ionic strength, pH levels, the presence of divalent ions, the type, and the concentration of organic matter in the environment, as well as the overall quantity of engineered nanoparticles present [18,19]. Moreover, SP-ICP-MS analysis renders insights into nanoparticle behavior, suggesting complex relationships between their number concentration, mass, and dissolution dynamics. This analytical approach underscores how aggregation and dissolution dynamics are intricately linked to nanoparticle concentration and size variations [20]. In addition, studies have indicated that nanoparticle aggregation can intensify particle accessibility to biomass or ingestion rates, possibly leading to increased bioaccumulation within ecosystems [21, 22]. Invertebrates show the ability to bioaccumulate nanoparticles. For example, silver nanoparticles were found to be internalized into the gut epithelial cells of the estuarine polychaete *Nereis ~~diversocolor~~ diversicolor* [23]. Khan et al. further analyzed the bioaccumulation designs of silver nanoparticles functionalized with PVP, PEG, and citrate, compared to dissolved silver, in *Daphnia magna* and *Lumbriculus variegatus* [24].

When engineered nanomaterials are introduced into the environment, they can interact with the food or diet of animals and other organisms by binding with food material through aggregation and sorption processes. Therefore, assessing the dietary exposure of nanomaterials and their biological effects is correspondingly important for assessing ecological and human health risks. Croteau et al. found that isotopically labeled foodborne zinc oxide nanoparticles were effectively assimilated by freshwater snails. Bioaccumulation and toxicity remained unaffected ~~inspite~~ in spiteof agglomeration, resulting in reduced food consumption and impaired digestion. Accordingly, developmental processes such as growth and reproduction were impacted, possibly leading to population and community changes [25]. Additionally, Croteau et al. reported the bioaccumulation and toxicity of copper oxide nanoparticles in the freshwater invertebrate *Lymnaea stagnalis* following both waterborne and foodborne exposure. They concluded that copper oxide nanoparticles ingested through diet are more straightaway harmful compared to those absorbed through water exposure [21]. This study spotlighted the importance of chronic toxicity assessments in evaluating the environmental risks of nanoparticles. This study highlighted the importance of chronic toxicity assessments in evaluating the environmental risks connected with nanoparticles [26].

1.2 Environmental continuity and mobility

Nanomaterials are extremely resistant to degradation, allowing them to continue in the environment for prolonged periods. Their small size and unique properties enable them to move easily through the air, water, and soil, alleviate widespread distribution, and thus increase the potential for environmental contamination. Once released, nanomaterials can travel long distances, spreading their impact far from the source and complicating efforts to include and rationalize their effects. The environmental durability of nanomaterials, meaning their resistance to modification and degradation, is influenced by the chemical constitution of both their core and surface materials. While many nanomaterials may continue in their original particulate form for prolonged periods, this should not be universally assumed.

Sulfidation of nanoparticles, for instance, modifies their surface chemistry, aggregation state, and charge, which in turn affects their ability to liberate toxic Ag^+ ions [27]. This process directly impacts their durability and toxicity, demonstrating how chemical interactions can change the behavior of nanomaterials in the environment. In addition, nanomaterials interact with humic substances and natural organic matter, resulting in a nanoscale coating akin to protein coronas observed in mammalian systems [28]. This coating importantly changes the aggregation, deposition, and toxic characteristics of nanomaterials, further perplexing their environmental and biological interactions [29].

Furthermore, aggregation can influence the persistence of nanomaterials by potentially revealing their dissolution or degradation, although taking place under various environmental conditions compared to when the nanoparticles are dispersed. This interaction between aggregation and environmental persistence highlights the complexness of anticipating nanomaterial behavior. The solubility of many nanoparticles is also critical, as it determines their interaction with biological systems like bulk chemical agents. Hence, toxicological testing procedures suitable for soluble nanoparticles can be efficaciously applied, while recognizing the unparalleled challenges posed by less soluble or degradable nanoparticles. The biological effects of biodegradable nanoparticles depend on their structural wholeness and degradation byproducts. In contrast, nanoparticles with very low solubility or degradability may accumulate within biological systems, elevating concerns about elongated retention [30]. In humans, nanoparticles are excreted via the renal and hepatobiliary systems, which must operate expeditiously within clinical approval timelines. Therefore, engineered drug-conjugated nanoparticles must be configured to evade speedy elimination and ascertain sustained residence in the body, balancing effectivity and safety in medical applications [31]. This interrelated understanding of nanomaterial behavior in different concerns is pivotal for processing efficacious environmental and health risk assessments.

It has been overviewed that nanoparticles can swiftly enter the aquatic environment via mechanisms like industrial discharges, the release of wastewater treatment effluents, or runoff from soil surfaces [32]. Once introduced into water bodies, the fate of these nanomaterials is controlled by multiple factors. These include their inclination to aggregate, accumulate, diffuse, and interact with various compounds, including aquatic organisms. Furthermore, biodegradation processes namely, aerobic and anaerobic degradation, photolysis, and hydrolysis also play pivotal roles in deciding their environmental behavior and impact [33]. In freshwater environments, nanoparticles incline to aggregate and settle into sediment layers, projecting risks to sediment-dwelling organisms. Meantime, in marine ecosystems, nanoparticles may accumulate at certain interfaces between cold and warm currents, potentially endangering species such as tuna [34]. These findings also highlighted how engineered nanoparticles such as TiO_2 and silver nanoparticles, can follow aquatic organism feeding patterns and adhere to algal cell walls [35]. The destiny and transport of engineered nanomaterials in water depend importantly on their stability: larger aggregates settle quickly, reducing mobility and availability, whereas smaller, well-dispersed aggregates airs higher risks because of increased mobility. Though research on engineered nanomaterials formed in natural water systems is restricted, aggregation remains a common phenomenon that reduces surface area and thus limiting reactivity. Factors like natural organic matter content and pH levels are crucial in influencing engineered nanomaterials behavior in an aqueous environment [36].

2. Lifecycle Environmental Footprint

A new conception to environmental impact is introduced because of the typical characteristics of nanomaterials. The physico-chemical reactivity of these nanostructures are crucial and projects possible risks to human health and the environment. These nano entities are produced for a wide range of devices and systems, including electronics, sensors, and nanomedicine, which have been acquired from advanced technological applications via novel synthesis and fabrication methods. Fundamentally, the widely used synthesis techniques are categorized into two main types, namely top-down and bottom-up. The top- down conceptualization involves fragmentation of larger bulk materials into nanoparticles through physical or mechanical way. On the other hand, bottom-up conceptualization involves controlled growth of nanoparticles from atomic or molecular precursors. In this method, nanoparticles are formed by assembling atoms and molecules from smaller building blocks. Typically, these approaches can be categorized into three main methods: solid-phase, gaseous-phase, and liquid-phase techniques. Among these, the wet chemical method or liquid based methods are advantageous for producing a wide range of nanomaterials with precise control over their size, shape, and morphology [37]. These techniques importantly spread out the practical implementation of nanotechnology, excavating a wide range of prospective applications.

2.1 Hydrothermal synthesis

The hydrothermal synthesis involves the formation of especially metal oxide nanoparticles with high purity and specific properties. The technique is valued for its ability to precisely control crystal structure and growth, making it ideal for several advanced applications [38].

2.2 Chemical reduction technique

This is an effective wet chemical tool, which utilizes a chemical reducing agent for synthesizing zero-valent nanoparticles. The aim of reducing agent is to reduce metal ions from their salt forms to their metallic state. The technique is widely popular in both research and industry for synthesizing nanoparticles because of its effectiveness, ease of use, and ability to produce nanoparticles with specific properties customized for various applications [39].

2.3 Sol-Gel technique

This is a versatile chemical technique for producing metal oxides and polymers from liquid solutions. During this process, a controlled chemical reaction gradually transforms a solution (sol) into a solid state (gel). The ability to finely tune material properties makes the sol-gel method essential in modern materials science and engineering, with applications in catalysis, optics, and battery technologies [40]. Therefore, several techniques like chemical vapour deposition, hydrothermal synthesis, chemical reduction, sol-gel method and others are capable of producing materials with improved electrical conductivity, large surface area, optimal ion diffusion and allow for precise control over the formation of nanostructures. The chemicals utilized during the synthesis of nanoentities can pose risk through inhalation, skin contact, or ingestion as well as can contaminate ecosystems, affecting aquatic life and soil quality. In contrast, using chemicals during synthesis process is essential for advancing technology and achieving specific material properties [Figure 2; 40].

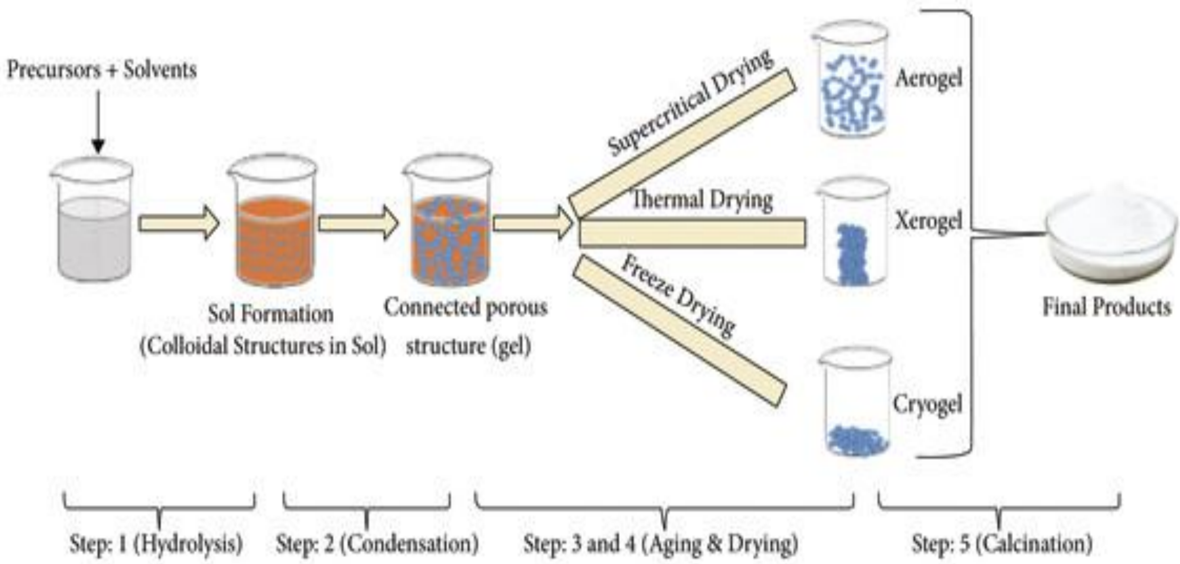


Figure 2: Synthesis process pre-requisite for advancing technology and achieving specific material properties

The unique features of nanomaterials enable their release into the environment at different stages and via various pathways. Additionally, the risks connected with the use of nanomaterials are ascertained by the processes that control their transport between installations and areas, their movement through the food chain, and the transformations they go through once released [41]. Hence, it is indispensable to evaluate the life cycle of nanoparticles, from production to disposal, to interpret their environmental impact comprehensively.

2.4. Models for assessment of nanoparticle emission

The evaluation of contaminants in the environment has been directed by various environmental models and tactics. Among the most frequently utilized models are Material Flow Analysis (MFA) and Environmental Fate Models (EFM). MFA examines emissions during the product lifecycle and their final deposition locations, while EFM explains how NPs are transported, transformed, and degraded when emitted into different environmental compartments [42].

(a) Material Flow Analysis (MFA)

Material Flow Analysis (MFA) purposes as a technical system to trail the flow of nanomaterials from their production stage via their final lifecycle stage. MFA envisages the environmental impact projected by emissions into many compartments such as water treatment plants, recycling facilities and others [41]. Although this model symbolizes nanoparticles by their shape and size, it does not provide definite information about nanoparticle concentrations in the environment [43].

(b) Environmental Fate Model (EFM)

Environmental Fate Models (EFM) envisage the behavior of substances within environmental compartments, including air, water, and soil. The EFM model integrates numerous models, one of ~~that~~ which is equilibrium model and is observed as an extension of the Material Flow Analysis (MFA) model [**Figure 3**]. This model discourses engineered nanoparticles and organic chemicals in both solid-liquid and liquid-liquid phases, where a partition happens between dissolved molecules and particle deposition. For instance, in water partitioning, small particles dissolve more readily in solvents liable on the solvent selected for the nanoparticles [44].

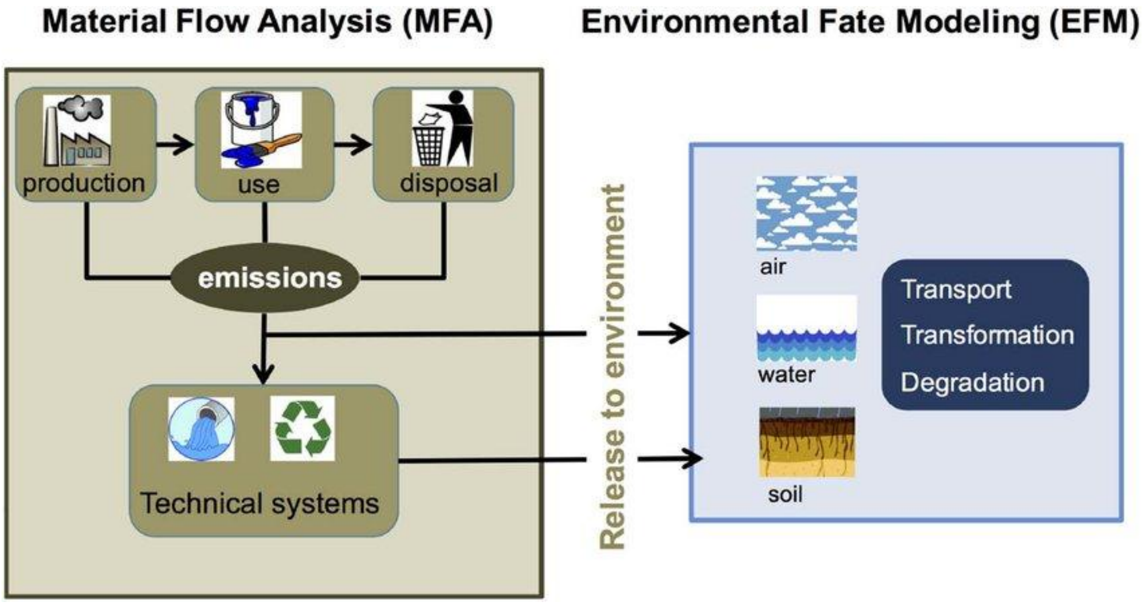


Figure 3: Elucidation of material flow analysis versus environmental flow model

3. Hazards and Challenges

The speedy progression and extensive application of nanomaterials bring potentials and noteworthy concerns vis-à-vis their impact on ecosystems and human health. One of the prime risks is the latent aggravation of ecological degradation. Because of their small size and exceptional properties, nanomaterials can accumulate in soil, water, and air, continuing for prolonged periods and possibly disrupting natural ecosystems. Their existence may vary soil fertility, affect plant growth, and thus harm beneficial organism's indispensable for ecological balance. In aquatic environments, nanomaterials can bioaccumulate organisms, projecting threats to aquatic life and thus impacting food chains [45].

It has been suggested that certain nanomaterials may persuade oxidative stress, inflammation, and cellular damage, contributing to respiratory disorders, skin disorders, and other health problems. Furthermore, the extensive use of nanomaterials in consumer products and industrial applications ~~rises~~ raises the likelihood of human exposure without an adequate understanding of their cumulative health impacts [46]. Addressing these risks requires comprehensive research to assess the environmental fate and toxicological profiles of nanomaterials, alongside robust regulatory frameworks to manage their production, use, and disposal. Proactive measures are essential to mitigate potential ecological harm and safeguard human health in the face of rapid technological advancement.

4. Sustainability in Nanomaterials

Notwithstanding distinctive physical and chemical properties of nanomaterials, they have the latent to adversely affect humans and the environment. The physical and chemical means for producing nanoparticles are often discouraged because of significant energy losses, the generation of large amounts of bio-waste and the production of harmful chemicals. Likewise, it is a complex challenge to assess and comprehend the effects of nanomaterials against ecosystem. This challenge necessitates the efforts of material scientists and physicists to understand particle structure, toxicologists and biologists to assess bioavailability and toxicity across different trophic levels and chemists to examine behaviour. Ecotoxicologists frequently treat nanomaterials as traditional chemicals assuming their behaviour is alike to that of soluble contaminants [47]. Nevertheless, quantifying the behaviour of nanomaterials in organisms and environmental media has confirmed more ~~challenging~~ challenges employing traditional procedures. Moreover, the speedy pace of nanomaterial risk research generates difficulties in providing a vibrant image of the current state of science and the inability to precisely evaluate environmental acquaintance concentration tends to high ambiguity levels in risk assessment.

Biogenic synthesis of nanoparticles is an environmentally friendly and workable approach of synthesising nanoparticles that eradicates the use of hazardous chemicals. This eco-friendly tactic utilizes bio-based materials like plants, microorganisms, and agro- waste for nanoparticle production [48]. The conversion of agricultural residues and agro-industrial bio-waste into bio-nanocatalysts, bio-nanosorbents, and other beneficial products is highly tempting [49]. Moreover, it has been revealed that green synthesis systems efficiently produce nanoparticles with desirable properties. These eco-friendly nanomaterials play a critical role in environmental remediation as antimicrobial agents, air pollution controllers, and in the purification of water and soil [50,51]. Their competence to eradicate contaminants and increase remediation processes pays significantly to environmental sustainability and hygiene. Furthermore, they hold considerable potential for cancer treatment, drug delivery systems, enlightening storage device efficiency, and reinforcing agricultural sustainability via crop shielding [52-55].

5. Environmental Remediation

Water pollution signifies a noteworthy threat to worldwide environmental health. The operative approaches for water remediation include precipitation, catalysis, adsorption, ozonation, and coagulation [**Figure 4;** 56]. The qualities of low toxicity, high efficiency reflected by catalysis and adsorption practices make them necessary for wastewater treatment. Biogenic synthesized nanoparticles play a vital role in eliminating harmful pollutants from industrial sources because of remarkable adsorption and catalytic competence.

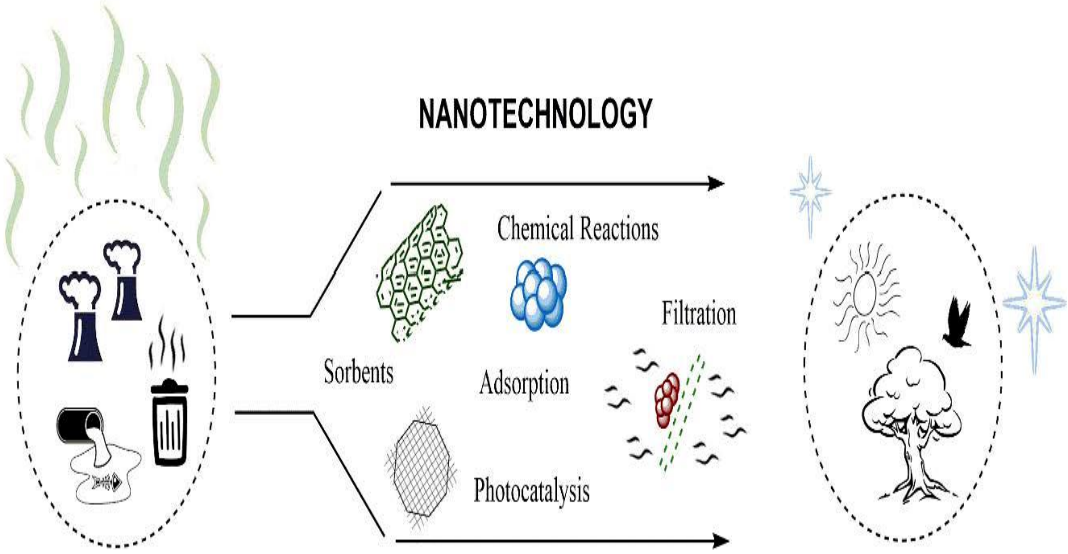


Figure 4: Picturization of environmental remediation through nanotechnology

6. Soil Remediation

Soil pollution has been disadvantageous to human health and ecosystems. Numerous approaches including excavation and ex situ treatment have been employed to discourse soil pollution. Though, due to the time-consuming and toxic nature of these systems, in situ treatments have been accepted to remediate contaminants, namely, dyes and heavy metals in the soil. Moreover, challenges facing Nano Environmental, Health, and Safety (EHS) research comprise recognizing nanomaterials in biological and environmental matrices, predicting their environmental fate, evaluating their threats, and eventually formulating quantitative risk evaluations [**Figure 5**; 57].

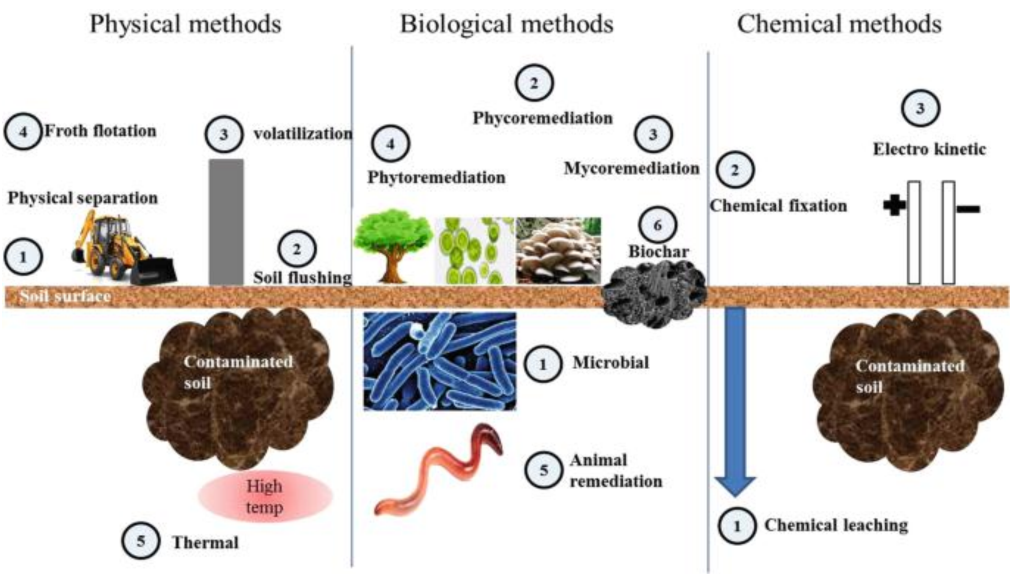


Figure 5: Elucidation of soil remediation

7. Life Cycle Assessment Methodologies

An effective tool like Life Cycle Assessment (LCA) can offer a profound apprehension of potential environmental issues and help ensure the ecological sustainability of nanomaterials [58-61]. By providing a comprehensive framework for evaluating the environmental impacts of a product throughout its life cycle, LCA identifies the materials used-up, energy utilized, and emissions released into the environment [62,63]. LCA is an internationally standardized methodological analysis, established by the International Organization for Standardization (ISO) 14040, comprising four phases: (a) Goal and scope definition, (b) Life cycle inventory analysis, (c) life cycle impact assessment, and (d) life cycle interpretation. This methodology was developed to measure the environmental impact of products and related processes [64-67]. This assessment comprehends various scopes viz. cradle-to-gate (from raw materials to factory gate), gate-to-gate (focusing solely on manufacturing processes), or cradle-to-grave (from raw materials to disposal).

The aim and scope definition outlines crucial determination that can frequently be subjective. This includes ground for conducting the LCA, an accurate definition of the product and its life cycle, and a description of the system's extremities. System extremities represent what is enclosed in the assessment and what is excluded. For example, minor ingredients that have a nominal impact on the overall footmark may be excluded from the study scope, hence defining the system extremities. During the inventory analysis of extractions and emissions, all environmental inputs and outputs connected to a product or service are examined [67-69].

Conclusion and Future Perspectives

The environmental impact of nanomaterials cannot be disregarded despite their technological progressions in numerous sectors. It is indispensable to address apprehensions like nanoparticle release, persistence, and bioaccumulation to prevent ecological degradation and latent health risks. Nanomaterials offer noteworthy advantages across various industries due to their exceptional properties and multipurpose applications. The factors like potential release of nanomaterials into the environment, and their persistence and bioaccumulation highlight the dual-edged nature of nanomaterials. Life cycle assessment (LCA) practices provide valuable insights into the environmental hotspots of nanomaterial production. By evaluating the environmental impacts at each stage of the lifecycle, LCA can guide strategies for improvement and thus help identify areas where intercessions can be most effective. Hence, the incorporation of environmental considerations from the design and synthesis stage through to the adoption of green manufacturing procedures and stringent regulations necessitates attaining sustainability in nanomaterials. This balanced tactic will enable to harness the benefits of nanomaterials while conserving ecological integrity and protecting human health for forthcoming generations.

Acknowledgments

Throughout moral support and cooperation from Chairman Mr. Pawan Singh Chauhan, Vice Chairman Mr. Piyush Singh Chauhan and the Board of Directors of S.R. Institute of Management and Technology, Lucknow, U.P., India, for accomplishing the present piece of work, is duly acknowledged.

Competing interests

The authors declare no competing interests.

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