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APPROACHES, CHALLENGES, AND PROSPECTS OF LIFE CYCLE ASSESSMENT APPLIED IN NANO BIOREMEDIATION OF CONTAMINATED SITES

G. Pandey[1,✉], S. Bajpai[2], S. Tripathi[3], Reeta Chauhan[4] and Pratima Sharma[4]
[1]Department of Chemistry, SRM -IST, Delhi- NCR Campus, Ghaziabad, 201204, (UP) India
[2]Department of Chemistry, Amity School of Applied Sciences, Amity University, Lucknow, 226010, (UP) India
[3]Department of Chemistry, United College of Engineering and Research, Knowledge Park III, Greater Noida, 201310, (UP) India
[4]Rajkumar Goel Institute of Technology, Ghaziabad, 201003, (UP) India
✉Corresponding Author: garimapandey.pandey8@gmail.com

ABSTRACT
The developments in the field of nanotechnology have facilitated new advances in almost every field out of which some are successfullybeen adopted and promoted whereas some are in the laboratory phase only. Due to their modifiable physical, chemical, and surface properties, nanoparticles/materials have attracted bulbous attention. To serve the demands of the ever-increasing population, rapid industrialization, and urbanization, the use of agrochemicals is being practiced globally which is increasing the contamination in the environment and affecting plants, animals, humans, and microorganisms. Researchers and environmentalists over the globe are working towards eco-friendly and cost-effective routes to eradicate contaminants from the environment. One such method is nano bioremediation wherein biologically synthesized nanoparticles/materials are employed for remediating the contaminants and this method has shown very encouraging outcomes. Along with the positive outcomes, nano bioremediation also brings in apprehensions about the impending effects of nanoparticles/materials on the environment through their life span. A life cycle assessment study is an inclusive instrument for studying the health and environmental impacts of practice, product or material all through its whole lifespan. Life cycle assessment on nanomaterials particles employed for bioremediation is performed with some modifications in principles in order to make them applicable to extraordinary characteristics of nanoscale dimensions.
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INTRODUCTION

Nanotechnology is a revolutionary technology that has the capability of transforming our approaches toward various life problems by interconnecting numerous research areas. Nanotechnology encompasses the designing, creation, categorization, and application of particles, structures, or materials at the nanoscale.[1-4] Materials (solitary particles or agglomerates) with dimensions underneath 100 nm are typically been demarcated as nanomaterials.[5,6] The nano-dimensions, morphology, increased mobility, and higher specific surface area of these materials induce specific properties in nanomaterials making their applications in almost each and every area ranging from physical, chemical, biological, electronics, and agricultural, construction, cosmetics, security, textile, etc.[7,8] The unwarranted industrial growth, chemical spills, discharge of domestic wastes, and agricultural runoff, without following precautionary norms has led to the accumulation of harmful substances like heavy metals, non-biodegradable solid wastes, and hazardous chemicals into the air, soil, and water bodies.[9,10] These contaminants disturb the water quality parameters, depreciate the structure, vigor, and productiveness of soil and deteriorate human, animal, and plant health in and around the contaminated area.[11] Various technologies are employed in order to decontaminate the affected areas and bioremediation is considered a green and sustainable method for decontamination. Bioremediation is the process of decontamination of environmental pollutants by using microorganisms and the products based on microorganisms and when

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nanotechnology works in amalgamation with bioremediation it is known as nano bioremediation.[12-15] The nano-bioremediation facilitates the sustainable and cost-effective biodegradation of environmental contaminants either by using the nanomaterial directly or by using them in the combination with microorganisms or microbial enzymes. The introduction of new technology in the market also brings in new challenges and nano-bioremediation is not exempted from this.[16-18]The remarkable benefits of nanomaterials are increasing their market at a very fast pace and this is bringing in issues related to human and environmental health.[19,20] The applications of nanotechnology also bring in the insecurities, ambiguities, health, environment, and safety issues of new technology. All through its life cycle, a nano product discharge nanoparticles into the environment, exposing the researchers, workers, consumers, and environment to impending hazards.[21] Moreover, from an ethical perspective, also it is imperative to recognize the cumulative market and societal impact of every manufactured good.[22,23]Because of their diverse applications and a large number of varieties, it is challenging to fully evaluate the fate of nanoparticles during their life cycle. One of the specific challenges while assessing nanomaterials is that fundamentally every nanomaterial is different from each other, and once released from a nano-based product, they can get transmuted into various other forms all through their life cycle.[24] The remarkable physicochemical properties of nanomaterials like size, composition, shape, and solubility, have a substantial impact on the toxicity and the fate of released nanoparticles in the environment.[25] Though the risks associated are not much known and the rules and guidelines governing nanotechnology are still not adequately designed and executed. The utilization of nanomaterials for bioremediation consists of removing the contamination from soil, water, and the environment by using biologically synthesized nanomaterials.[26] With the advancements in the field of nano-bioremediation, the concerns about the sustainability of the process are becoming the prime issue for researchers.[27,28] The sustainability of the methods, products, and technologies employed for nano-bioremediation can be assessed by various methods and LCA is a prominent one of them covering the full life span analysis.[29,30] Marketable produce has to be safe and sound, not only for every living being in contact but also for the environment. The process of Life Cycle Assessment is a broad, comprehensive, and compendious approach that is used for evaluating the ecological effects accompanying produce through its cradle-to-grave assessment to inspect its effects on the environment and the energy requirements. The life cycle assessment runs through all the phases of the lifespan of a product covering the initial phase of mining of raw materials, their processing, manufacturing, industrialization, marketing, supply, consumption, discarding, recycling, and then reusing.[31]For assessing overall sustainability it is necessary to understand and recognize the social and economic effects and aspects of nanomaterials used for the remediation of contaminated sites. This chapter purposes to perform a methodical analysis of nano-bioremediation and their LCA studies to ensure the sustainability of nanoparticles intended for remediating the contaminated locates. Also, future challenges and recommendations to ensure the success of nanotechnologies for bioremediation through LCA studies will be reviewed in this chapter.

Nano-Bioremediation

The uncontrolled urbanization and industrial development, in order to fulfill the demand and supply equilibrium for the agricultural needs to the ever-increasing population, is increasing the contamination of the environment.[32] The contaminants like heavy metals and their compounds, agrochemicals, hydrocarbons, drugs, solid wastes, and inorganic compounds, etc. (Figure-1) are posing serious threats to ecological balance, contamination of soil, air, water, and the health of humans, animals, and plants.[33,34] Extensive research and various physio-chemical technologies, for instance, adsorption, precipitation, electrical coagulation electro-chemical treatments, are being employed for the degradation of these contaminants still, there is an urgent requirement for a sustainable environment-friendly economically efficient approach to remediate the environmental contaminants.[35] Nearly all the existing conventional remediation practices follow the usual ex-situ methodology and are highly expensive, energy exhaustive, and may possibly leave harmful residue requiring further management. Bioremediation is one such technology that can help in decontamination in a sustainable manner.

Bioremediation utilizes green plants, microbes, or enzymes obtained from them, in an appropriate environment for removing contamination.[36,37] The amalgamation of bioremediation and nanobiotechnology for environmental decontamination is known as nanobioremediation. Nanotechnology deals with controlling and designing particles/materials at the nanoscale. The nano-scale dimension, high surface area, cost-effectiveness, efficiency, unique catalytic behavior, improved magnetic properties, and eco-friendly nature of nanoparticle materials make them highly useful in the remediation of contaminated sites.[38,39]

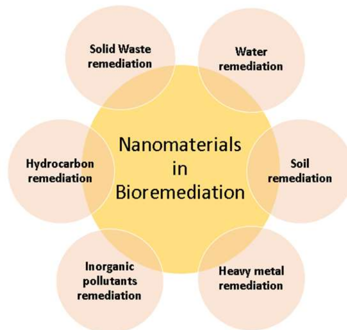

Fig.-1: Role of Nanomaterials for Bioremediation of Contaminated Sites

The key applications of nanotechnology for environmental remediation consist of the following steps:[40,41]

1. Detection of contamination/ pollution,
2. Prevention of contamination/ pollution
3. Remediation of contamination/ pollution

Various research works based on the type of the contaminant and its nano-remedy have been reported and patented by scientists worldwide. Some of these patented works are been successfully adopted and marketed whereas some are still in their laboratory stage. Table-1presents a list of works been patented in nano bioremediation.

Table-1: Patents Assigned for Nanomaterials Used for Bioremediation

Patent numbers; Reference	Patented nanomaterial	Remediated contaminant	Name of the Author
A mixture	A mixture of modified clay minerals, carbon nanotubes, and lime.	Pb-Cd and Pb-CdS composite	Chen, M. *et al.*, 2015; Gao *et al.*, 2014 [42,43]
CN106475052-A CN105950155-A CN105950180-A CN105950181-A	A mixture of activated carbon, lime powder, Hydroxylapatite, nano-Si, gravel, and CaO_2	heavy metals from the soil, toxicity, and organic persulfates from water	Lv*et al.*, 2017; Ming *et al.*, 2016a, 2016b, 2016c [44-47]
CN105505397-A CN105505398-A CN105441082-A	a mixture of fly-ash, BaO NPs, bentonite, ferric aluminum silicate polymer, $Mg(NO_3)_2$, stachydrine, dimethylol urea $CaAl_2O_4$, phospholipid, and magnesium aluminosilicate	Lead and Copper from soil	Cheng , and Zhong, 2015a, 2015b, 2015c [48-50]
WO2014168728-A1 WO2013173734-A1	zero-valent Fe NPs, Fe NPs coated with Ca-alginate, plant-based amphiphilic copolymer	agri- contaminants, heavy metals	Bezbaruah, *et al.*, 2015[51] Chisholm *et al.*, 2014 [52]
CN105733593-A CN105733588-A CN105647539-A CN105598158-A	Microbial assembly, Fe-bio-char substance, biomaterial of P-C	Cd and As from soil	Chai *et al.*, 2016a, 2016b, 2016c, 2016d [53-56]
CN106430598-A CN206051687-U	Nanocomposite material in the ecological bag	Heavy metals from the soil	Feng, *et al.*, 2016a, 2016b[57,58]
CN104801540-A CN104807762-A CN104801534-A	Polymer coated zero-valent Fe NPs, magnetic nanomaterial coated with organic substance	heavy metals from the soil	Li, and Liu, 2015a, 2015b,2015c [59-61]

CN105131960-A CN105013811-A CN103157810-A	Bio-char material, composites, Ni-Fe NPs	Pb and Cr from soil, brominated diphenyl ethers	Fang and Yang 2015[62] Fang and Su 2015 [63] Fang and Xie 2013 [64]

The specific nano-scale characteristics of nanomaterials /particles are well adaptable for in-situ application making nanotechnology, one of the best-suited approaches for providing efficient and inventive solutions to these challenges of decontaminating the environment by remediating contaminants into their eco-friendly forms.[65, 66, 67]

Ins and Outs of Nanomaterials During Bioremediation

Nano bioremediation is drawing foremost attention as a sustainable and adaptable method for environmental decontamination. Nano bioremediation covers three major aspects of sensing the contamination, green synthesis of nanomaterials, and their in-situ or ex-situ applications for bioremediation.[68,70]Nano bioremediation is pragmatic for the elimination of heavy metals, agrochemicals, and pharmacological wastes, from the contaminated sites of soil, air, and water.[71] Nanoparticles formed by CNTs, quantum dots, magnetic nanoparticles, nanoscale zeolites, noble metal nanomaterials, dendrimer enzymes, nanoscale elemental metal, and metal-oxide nanoparticles are generally used for water and soil remediation.[72-74] The low solubility, nominal effect of the environment, and no secondary contamination of nanoscale elemental metals and metal oxide nanoparticles have made them accepted and utilized as sorbents for removing heavy metal contamination. The biocompatibility, creation of an inert environment, retention of inherent properties, and bioactivities of enzymes in enzyme-mediated nano bioremediation are gradually being accepted and adopted as a sustainable method for decontamination[75-77] The selection of nanomaterial for bioremediation of contaminated sites is a very crucial step as they might pose threat to the microbes been used for bioremediation.[78] Nano-membranes and nano-adsorbents have been found very effective in removing biological contaminants, synthetic chemicals, and heavy metals from contaminated water.[79,80] For the decontamination of soil nanoparticles/materials are used as mobilizers, sorbents, or photocatalysts to remove the sewage, agricultural waste, and inadvertently discharged waste or residues from industries. Nanoparticles being exploited for bioremediation are listed in Table-2.

Table-2: Biologically Synthesized Nanoparticles/Materials Exploited for Nanobioremediation[81,82,83]

Name of the nanoparticle	Decontamination Site	Name of the contamination
Cu NPs	Water	Organic compounds (Dichloromethane), Organic dyes (Methylene blue, Methyl Orange)
Ag NPs	Water	Organic dyes (Methylene blue, Congo red), p-nitrophenol, effluent from textile industries
Au NPs	Water	Dye effluents (tertiary), p-nitrophenol, Methylene blue
Zn NPs	Water	Heavy metals Cd(II) metal, Organic compounds Phenol, p-chloro catechol, Formaldehyde, Malachite green, Rhodamine B, Resorcinol, EBT, Acid orange 7
Fe NPs	Water, Soil	Heavy metals (Cr, As, U, Hg,Cu,Pb,Cd, Co, Ni), Organic compounds (Decarbominated diphenyl ether, Chlorobenzene, Pyrene, furans, Di and Pentachlorophenol, Polychlorinated biphenyls, RDX, atrazine), Gammaxene,TNT, DDT, vinyl chloride,pathogens
Ti NPs	Water	Organic compounds (Xylene, Ethylbenzene, Benzene, toluene, chloroethanes,)
Co NPs	Water	Lithium
Ca alginate NPs	Water	Oil slicks, chromium
CdS NPs	Water	Cadmium
Pd NPs	Water	Nitroarenes
SnO_2 NPs	Water	Nitrophenor

Though nano bioremediation is a widely studied and researched technology, still it is the need of the hour to concentrate on some of the key aspects of regulatory tailbacks, applicability, geographical variety, and data comparability to remove common cynicism and gain the broad recognition and acceptance.[84,85]The effect of the Nanoparticles on water and soil ecosystem and on human and environmental health, is a significant matter to be noticed and addressed.[86,87]Though not much information about the toxicity of nanoparticles/materials is available and the unknowns will get discovered and reported through further studies in the future still numerous nanoparticles are been recognized to induce oxidative stress, cardio-vascular issues, tissue inflammation, and damage, carcinoma, genetic, biocidal, respiratory, and neurological disorders (Fig.-2) (Table-3)in humans and animals.[88-103]

Table-3: Impacts of Nanomaterials/Particles Used for Nano bioremediation

Nanomaterial	Organisms being affected
Fe	Bacteria, algae, invertebrates, genotoxicity, and cytotoxicity in humans
CNT	Bacteria, fish, invertebrates
Cu-Fe, Ag-Fe, Ni-Fe	Marine invertebrates, mammals, Bacteria, algae,
ZnO_2	Bacteria, invertebrates
TiO_2	mammals,
CdS_e	Water microbes,
CeO_2	humans
Cu NPs	Marine invertebrates, humans
Au NPs (rod-shaped)	keratinocyte cells in humans
Ag NPs	Genotoxicity in humans

Thus it is very much necessary to understand, analyze, and keep a record of the release and transport, grade of perseverance, fate in the environment, and the toxic effects of nanoparticles/materials created and employed for bioremediation.[104,105]

Release, Behaviour and Fate of Nanoparticles in Soil and Water

The behavior and fate of nanoparticles at the contaminated site (soil and water) is fundamentally been determined by their interaction with the environment based on their bio-availability, high reactivity, and extraordinary mobility.[106,107] The fate of nanoparticles in the environment is influenced by aggregation, flocculation, dispersion, diffusion, adsorption, degradation (abiotic or biotic), photolytic transformation, steric-stabilization, charge neutralization, and enhancement by the interaction between them (Fig.-2).[109,108]The structure of natural water and the colloidal organic substances present in soil have intricate effects on the mobility, activity, and stability of nanoparticles being used for remediation purposes.[109,110]

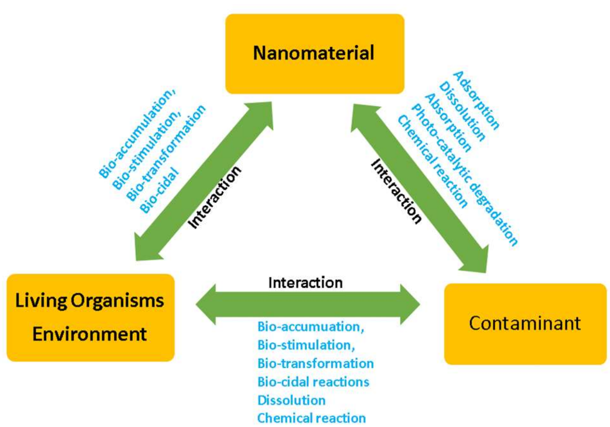

Fig.-2: The Reversible Interaction between Nanomaterial, Contaminants and Living Organisms and its Effects

During the process of nano remediation, nanoparticles can get released during following steps:

1. Synthesis of nanoparticle/material for bio remediation
2. Incorporation of nanoparticle/material at a remediation site
3. Aging of the nanoparticle/material used for bioremediation
4. End of Life of the nanoparticle/material

The LCA studies are very much necessary for the risk and safety assessment of nanoparticles/materials being employed for bioremediation.[111] It is very much important and essential to know the advantages of the nanomaterial being used that recognize when, how much and where the nanoparticle/material all through its life span can be hazardous to humans or the ecological balance of the remediation site.[112,113]To perform LCA studies on nanomaterials used for bioremediation firstly it is necessary to collect information about the safety, toxicity, risk issues associated, their stability, and degradability during the whole bioremediation process.[114] The LCA studies of nanomaterials being used for bioremediation involve the following steps.[115]

- Validating evident harms of the nanomaterial used.[116]
- Assessing the benefits of the concerned nanomaterial.[117]
- Carrying out a systematic research analysis of the toxicity of the nanomaterial.[118]
- Combining the results of LCA studies with those of toxicity and research analysis.

Biosynthesis (Green Synthesis) of Nanoparticles

The incomparable magnetic, catalytic, optical, electronic, and mechanical characteristics of nanoparticles are enticing researchers to discover novel methods for their synthesis. Nanoparticles can be synthesized by several chemicals, physical, and biological approaches.[119,120]The physical approach of synthesis is extremely expensive while chemical ways struggle with the problems related to inaccurate structure, slow growth rate, and cause stern environmental hazards. Green synthesis (bio-synthesis) is an inventive, environmentally sustainable, cost-effective, and faster technique of synthesizing nanoparticles. By mixing an appropriate quantity of metal ions with phytoextracts (extracts from plants or microbes) inadequate reaction conditions.[121,122,123, 126]It has been reported that green synthesis (biosynthesis) methods have shown positive results in very mild reaction conditions like room temperature and the synthesized nanoparticles have shown to have a distinct structural, and physicochemical properties.[124,125]Nanoparticles being synthesized through green/biological methods are listed in Table-3.

Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is an approach for assessing the ingestion of resources and the waste discharges attributed to the life cycle of a product.[127-129] LCA is being acknowledged as a prevailing instrument and has thrived in the past decade to recognize impending life cycle impressions of nanotechnologies.[130,131] LCA is a vital instrument for evaluating environmental impacts related to all the phases of extracting the raw materials, their processing, and manufacturing of the desired product, its transport, usage, disposal, and recycling of a product. As per the definition given by ISO 14040[132], the technique for life cycle assessment exercise involves four stages (Fig.-3).

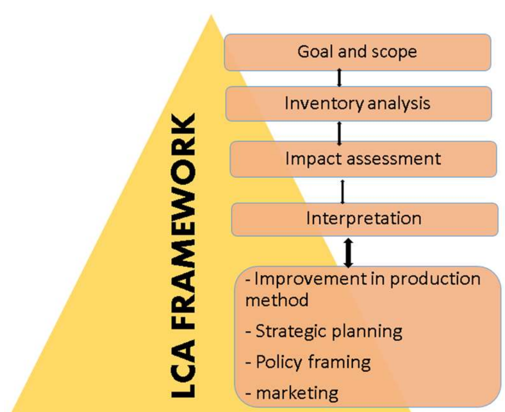

Fig.-3: Framework of Life Cycle Assessment Studies

1. Aim and opportunity definition
2. Investigation of inventory
3. impact valuation
4. Interpretation of outcomes
5. Strategic planning based on the findings

The Life Cycle Analysis (LCI) focuses on the collection of data, computational study, and summation of the results from the inventory examination to compute the pertinent input and output of a particular product[133]. This analytical method connects inventory figures with explicit environmental effect class as a marker for climate alteration. LCA can adequately answer a lot of issues related to the potential effects of nanotechnology. The exceptional physical and chemical properties of nanomaterials necessitate specific amendments in traditional LCA methodologies to make them applicable to nanomaterials. As per the 7-step LCA framework proposed by Walser *et al.*theUSEtox® model (UNEP-SETAC based toxicity model) is employed to make nanotechnology-specific adaptations.[134]As the USEtox® is a mode based on the mass of substances, it is very much essential to apply unit conversions in order to acknowledge the complex physiochemical properties of nanomaterials.[135,136]

Life Cycle Assessment Applied to Nanobioremediation

The LCA studies on nanotechnology include studies on effects on climate, toxicological trauma on environmental health and human wellbeing, exhaustion of natural resources, and numerous other effects.[137] Titanium oxide nanoparticles, quantum dots, CNTs, and SWNTs are the majorly studied nanomaterials in the light of LCA methodology though not many LCA studies have been performed on nanomaterieals.[138, 139,140] Table-4 provides a list of nanomaterials on which the LCA has been performed.Life cycle assessment of nanomaterials being used for nanobioremediation is very much necessary to recognize their entire positive and negative possible environmental encumbers and to avert environmental threats.[141] It’s the toxicity of nanomaterials that is of utmost concern for the sake of the life cycle assessment.[142] Therefore, it is very much necessary to institute a complete indulgence of all the positive and negative effects of nanomaterials on the environment and living beings over their complete life cycles and LCA can play a vital role to accomplish this.[143] Concerning the application of LCA on nanomaterials and nanotechnology[144-146] there are three key aspects to be analyzed:

1. Why is it required to perform LCA on nanomaterial?
2. Who would be performing LCA on nanomaterial?
3. What would be the advantages of performing LCA for various contributors?

Table-4: Nanomaterialsfor Which LCA Has Been Performed

Gold nanoparticles	(Pati *et al.*, 2016) [147]
Carbon nanoparticle	(Kushnir and Sanden, 2008) [148]
Starch nanocrystals, organically modified nanoclay	(LeCorre*et al.*, 2012) [149]
Nano TiO2	(Grubb and Bakshi,2010) [150]
Carbon nanotube	(Eckelman*et al.*, 2012)[151]
Nanosilver	(Walser *et al.*, 2011) [152]
Cadmium selenide	(Sengul and Theis, 2010) [153]
Nanoclay,	(Joshi, 2008) [154]
Nano-Silica-Modified Asphalt Mixtures	(Solomon *et al.*, 2019) [155]
SWCNT and MWCNT	(Healy *et al.*, 2008;Gilbertson*et al.*, 2016) [156,157]
Ag nanoparticles	(Geranio*et al.*,2009;Künniger*et al.*,2010)[158,159]
CuO nanoparticles	(Fan *et al.*, 2020) [160]
Zero valent nano Fe	(Visentin*et al.*, 2020) [161]
semiconductor crystals and quantum dots	(Steinfeldt*et al.*, 2004) [162]
nano-varnish	(Steinfeldt*et al.*, 2004) [162]
clay polypropylene nano-composite	(Lloyd and Lave, 2003) [163]
nano-scale platinum-group metal	(Lloyd *et al.*,2005) [92]
cellulose nanosponges (CNSs)	(Bartolozzi*et al.*, 2020) [129]

Why is it Required to Perform LCA on Nanomaterials?

LCA studies performed on nano-based products can respond to questions on the environmental impacts of nanoproducts, for instance.[164]

- How much is the energy efficiency of a nano product and how does its life cycle weights against a conventional product?[165]

- What are the Concerns related to end-of-life managementofnanomaterials.[166]
- What are the toxicity effects of nanomaterials?[167, 168]
- How the studies on toxicological effects of nanomaterials can be incorporated into LCA studies?
- Is there any agreement between the impending toxic effects of nanomaterials on human beings and on the environment?[169]
- What is the geological impact of a nanoproduct?[170]

Who Would Be Performing LCA on Nanomaterials?

LCA studies on nanotechnology and nano-based products will principally be carried out by the businesses themselves, the industry experts, and the people from academia.[171]

What Would Be the Advantages of Performing LCA?

- LCA studies can assist in drafting policies and statutes for human and environmental health and well-being.[172]
- LCA results can be taken into account while procuring nanotechnology-based machinery, processes, and products.[173]
- Early investigation of the positive and negative effects of nano products on the environment will be beneficial in implementing the policy of sustainable, secure, and accountable development.[171]
- LCA results can be used for refining, directing, guiding research, and development activities for developing economically effective processes to produce eco-friendly nanoproducts.[174]
- LCA results can help researchers and industries forecast and avoid, the likely environmental troubles of their product throughout its production, marketing, operations, and disposal.[175]
- LCA results can facilitate framing and adopting strategic legislative steps to find better investment opportunities and manufacturing capabilities.

Phases of LCA Studies of Nano Bioremediation

Inventory

This phase of LCA of nano bioremediation involves the identification and quantification of every input and output of all the practices involved. Because of the non-availability of primary data due to privacy constraints, the LCA studies utilize the secondary data sourced from patents, publications, waste treatment industries, raw material suppliers, and government and non-government reports.[176,177] The eco-invent records obtained from the up-to-date version of the Simapro software can also provide data related to the mining process of raw materials, and the fuel and water requirements in the production of nanomaterials required for nano bioremediation. All the statistics collected for the inventory phase of LCA are chosen with the consideration of the geographical settings of the place of production.[178]

Impact Assessment

The categories selected for the impact assessment of nano bioremediation are the effects on resources, climate changes, and effect on human and environmental health. The impact assessment in LCA studies calculates the possible health impacts of a product on human and environmental health. Equation (1) is used to calculate the impact score of every impact class.[179,180]

$$IS=\sum_{I,j} m_{i,j} * CF_i \quad (1)$$

Where, m = amount of release or resources consumed
i = specific substance emitted
j = a phase in the life-cycle of the product
CF = characterization factor
IS = impact score

A CF provides a quantifiable potency of the materials been released with respect to the impact type in consideration.[146] The assessment of human and environmental toxicity necessitates the collection of statistics on the extent of exposure, toxicity, and environmental fate, extent for the quantitative as well as the qualitative assessment of the entire sequence of cause and effects.[181,182] For all such assessments, the

USEtox® model has been developed to calculate the CF for the assessed material by using equation (2) as follows.

$$CF = FF .EF. SF \quad (2)$$

Where, FF (fate factor in days) = persistence on the material in a specific medium.
XF (exposure factor in days) = days -1, concentration of substance with consumption.
EF (cases/kg consumption) = relation between the amount of the substance consumed and toxic effects in case of human toxicity and the relation between the part of the species been affected and the mass of a substance.
CF = characterization factor.
The other most commonly used method for impact assessments in LCA studies is the SimaPro® methodology by the Impact 2002.[183,184]

Normalization

The LCA studies involve the evaluation of environmental and socio-economic indicators in multi-dimensions, therefore it is necessary to convert them into dimensional values which can be achieved by performing normalization of the results obtained from LCA studies.[185]

Interpretation

In this phase of LCA studies of nano bioremediation, results achieved from all the preceding phases are assessed with respect to the objectives and the scope of the study, thereafter appropriate recommendations and conclusions are made to produce the results.[186]

LCA Operational Problems to Deal With

A number of operational issues have to be addressed while performing LCA studies on nanoparticles/materials being used for bioremediation.[187]

- lack of figures and statistics related to nanoparticles/materials.
- Though "conventional" inventories are based on mass values, supplementary information pertinent to evaluating the exposure, effects, and fate of nanomaterials would be needed.[188]
- Toxicity effects of nanoparticles/materials.[189]
- Investigation of the issues related to ambiguity and sensitivity of nanoparticles/materials.
- Transformation of nanoparticles/materials in water and soil by dissolution, agglomeration, and sedimentation leading to change in surface properties.[190]

Future Prospects and Recommendations

Diverse methodologies have been adopted in order to contain the nano-specific characteristics during the phase of impact assessment in LCA studies. Different analytical models specific to the nanomaterial concerned were attempted to calculate the characterization factor (CF) for toxicity impact assessment in the environment and humans.[152] Walser *et al.* calculated the biocidal impact of Ag NPs by performing a literature survey and USES model, Eckelman*et al.*used the USEtox model for calculating freshwater toxicity of CNTs, Salieri *et al.*[191], applied the USEtox model for TiO_2 NPs. A new simulation tool known as Red-Nano, (equipped with a graphical user interface) was designed by Liu *et al.*, (2015)[192] by combining the benefits of MendNano (a modeling platform), and LearNano (life cycle inventory methodology). The graphical user interface of RedNano supports the LCA studies in the following manner:

1. It supports direct simulations through maps, Sanky diagrams, and graphs.
2. It takes into account the nanoscale-specific properties of nanomaterials (aggregation, suspension, sedimentation, change in properties, and structure), their environmental distribution, and simulations of weather conditions.
3. Determination of the discharge rate of nanoparticles in the environment by using primary data available in the literature, through LearNano.
4. RedNano is capable of creating a library of all the simulations for further LCA studies.
5. RedNano recognizes the kinetics of environmental release, proposed usage, and the environmental fate compartments of nanoparticles for LCA studies.

To perform a successful LCA of nanomaterials being used for bioremediation it is necessary to adopt certain steps based on the following suggestions:[193]

- To assess the reliability of LCA studies they should be reviewed critically.
- Collaboration with the industries and laboratories to acquire authentic data for LCA studies.
- Designing policies for LCA of nanomaterials and nanoproducts for bioremediation.
- Promoting and funding R&D activities.
- Using LCA to support promoting green purchasing in nano-bioremediation
- Utilizing LCA results in the design of cost-effective and better environment-friendly nanomaterials/products for bioremediation.
- Spreading awareness about the green nano-bioremediation by communicating LCA results to the agencies working.[194]

The inherent characteristics of the methods used for synthesizing nanomaterial/particles (use of scarce raw materials, toxic chemicals, low production yields, rigorous purification methods) generally make their resource and energy exhaustive. LCA studies when applied in the early stages of development can provide energetically efficient, cost-effective, less exhaustive eco-designed[195,196] solutions like designing macro materials from nanomaterials, retaining their porosity, and high surface area with better analysis and management of the release, transport, and fate in the environment for sustainable nano-bio remediation.[17] The lack of toxicity information[197] in LCA can be managed by integrating it with some other analytical methods like Risk Assessment (RA) [198-200], and a Multi-Criteria decision analysis (MCDA)to give nano-oriented assessment results.

CONCLUSION

The swift progression in innovations and technology has accelerated the growth of nanotechnology and a range of nanoparticles are being utilized to bring about the bio-degradation and removal of contaminants from the environment. Consequently, it is necessarily required to standardize the regulations for nanoparticles, identification, and management of risk factors throughout their life cycle. Therefore, there is an urgent need to adopt sophisticated diagnostic and systematic ways for the detection and categorization of nanomaterials and their environmental effects throughout their journey from cradle to grave. The dearth of the inventory figures related to nanomaterials because of constantly changing synthesis methods, privacy restraints, and the exploration of health and environmental effects are making the process of conducting LCA studies with nanomaterials a tedious task to perform. To understand the environmental consequences of a new product or a technology in a better way and to assess its relevance it is required to apply LCA methods in the initial phase of its development. Moreover, in order to understand the overall impact of nano bioremediation on the environment and humans, it is required to develop and include the impact assessment models along with further research on toxico-kinetics and bioaccumulation of nanoparticles in the LCA studies. In view of the fact that nanotechnology is a multibillion-dollar industry with global distribution, LCA studies can be performed only on a limited number of nanomaterial/products because an inclusive assessment of nanotechnology may result in oversimplification of results creating doubts greater than before. The results reveal that Vernonioside E and D are effective as anticancer through downregulation of EGFR and mTOR proteins.

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