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Nanotechnology in Context of Environment and Industrial Development: A Review

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Abstract

Climate change and sustainable development with context to environment has been one of the main concerns and challenges of 21st century. Industrialization and development go hand in hand, so we need to devise green synthetic routes so that our environment stays protected. In the past two decades, there has been significant advancement in the field of nanotechnology. Many cost-effective methods have been devised for large-scale production. Significant improvements have been made in synthetic routes as to make production more research friendly. In the 21st century, sustainable development is every country's responsibility. Industrialization, nanotechnology, and development go hand in hand, so we need to devise green synthetic routes so that our environment stays protected. One thing to be considered is that in the present era of industrialization, nanotechnology cannot be confined to research labs or small-scale enterprises. Nanotechnology has widely been used in various industries, namely, pharmaceutical industry to synthesize nanomedicines, in agriculture industry (carbon sequestration as one of the applications in agriculture), civil engineering, environmental remediation (nano sensors are being used to combat pollution), automobile industry, food industry, and even cosmetic industry. Nanotechnology has promoted the use of renewable energy by creating solar panels which are more efficient and cheaper. Silicon chips are being replaced by nanochips at atomic level in electronics industry. In food industry too, nano biosensors are being used to detect microbes, pathogens in the food and their antioxidant properties increase the shelf life of food. In this paper, how nanotechnology has played a significant role in combating pollution, carbon sequestration, phytoremediation, green chemistry and industrial applications with some potential industrial and environmental limitations have been discussed.

Keywords: Nanotechnology, environment, photocatalysis, carbon sequestration, phytoremediation, green chemistry

INTRODUCTION

As the world is progressing, significant changes are taking place in our technology. The need of the hour is to have these advances without having any compromise with the sustainability of our environment. Nanotechnology has had a significant impact on the research in the past two decades. Many synthetic routes have been devised by making use of nanotechnology. Nanoparticles have been prepared by devising green synthetic routes and these particles have significant role in combating pollution. They have the ability to remove the finest pollutants from air as well as water. Nanoparticles of zinc oxide (ZnO), copper oxide (CuO), cobalt oxide (CoO), and iron oxide (Fe_2O_3) [1–3] have photocatalytic properties. They can be used to decontaminate pollution caused by dyes from the water. Silver oxide (AgO) has great anti-microbial properties and is used for decontamination [4–9]. Many a time, nanocomposites are prepared by green synthetic routes using plant extracts instead of using chemically fabricated methods, which not only

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enhances their potentiality [10–12] but it is also highly beneficial for the environment as they are prepared by green technology means no harmful substances were released in the environment. The numerous properties of nanoparticles such as magnetic, antioxidants, antimicrobial, optical, photocatalytic, large surface to volume ratio, morphological make them potential players in sustainable and green development. In this paper how significant is nanotechnology in the context of environment and in the era of industrialization has been discussed [13–24].

Nanotechnology and Combating Pollution

In the ongoing scenario of urbanization and industrialization, a large amount of toxic gases are released in the atmosphere (NO_2, SO_2, CO_2, chlorofluoro carbons [CFCs], CO, etc.). Nanoparticles of Fe_2O_3, ZnO, CoO are well-known photocatalysts [25, 1, 2]. Dyes are well known water pollutants and hazardous for the environment. Their activity can be combated by using nanoparticles as photocatalysts. Sodium salt of benzidinediazo-bis-1-napthylamine-4-sulphonic acid, commonly known as Congo red dye, a well-known water pollutant when treated with nanoparticles, showed progressive degradation over a gradual period of time [26]. Since the nanoparticles have significant metal defects, they have semi-conducting properties. Photons generated as a result of irradiation by an electromagnetic source of light will excite atoms from the organic material on which these photons fall, and electrons from conduction band jump to valence band causing reduction and leaving holes. As a result of this, reactive oxygen species (ROS) are created, which are responsible for degradation activity in the organic material such as a dye or any other similar chemical [27–31].

Nanomaterials, due to their high surface to volume ratio, have accurate and significant monitoring character. Nanomaterials act has sensors of high precision and thus help in pollution prevention [32]. Adsorption process is used for this in which atoms, ions, molecules, or gases are adhered to a surface. A film of adsorbate is created on the surface of adsorbent. In adsorption the substance does not permeate to the bulk rather it lies on the surface. Nano adsorbents have been used significantly to combat this problem. The physical attributes of carbon nanostructures play important role in adsorption. Carbon based nanomaterials are used as adsorbents extensively like carbon nanotubes, fullerenes, graphene, and it has been reported that their efficacy is much more than that of activated carbon [33].

After the world had gone through the pandemic, in addition to detecting toxic gases as pollutants in the atmosphere, detection of bacteria and viruses is also important. Nano sensors are nano-scale devices which detect and respond to physical, chemical, or biological stimuli at a nanoscale. They are of different types: mechanical, chemical, biological, optical, and electrical [34, 35]. In case of detection of air pollutants (be it gases or particulate matter), signal is transduced as soon as the pollutant comes in contact with it. Then the nano sensors show sensitivity to the pollutants (as they have high surface to volume ratio) and selectivity (generally they are made of materials which have high affinity to the target) [35]. Then there is signal detection and the detected signal is measured appropriately [35]. In this way, pollutants can be detected and dealt with judiciously.

Soil pollution is another type of pollution concerning the environment. The improper disposal of the solid chemical waste, residues of industrial waste, e-waste, illegal mining increase the toxicity level of the soil. Heavy metals and plastic waste are non-degradable in nature and contaminate and increase the toxic levels of the soil. In this regard, heavy metal immobilization is carried out using nanoscale particles [36]. Iron oxide nanoparticles were introduced in contaminated water which had high concentrations of heavy metals. The contaminant concentrations were reduced immediately and iron oxide nanoparticles adsorbed heavy metals in acidic pH also [37].

Phytoremediation and Nanotechnology

It is the method in which plants and microbes in the soil are used to decrease toxicity caused by the contaminants in the environment. This process helps in increasing the soil fertility [30]. Nanoparticles are useful in remediation process as they can rapidly penetrate (due to their large surface to volume ratio) in the contaminated areas [18]. The mechanism of phytoremediation involves various processes, such as the following:

a. *Phytoextraction:* It involves removal of heavy elements from the soil. Indian mustard (*Brassica juncea*) is known to remove Pb from the soil while lettuce (*Lactuca sativa*) is known to remove Ni, Co, and Fe [38].
b. *Phytodegradation:* It involves conversion of organic contaminants into simpler compounds. Indian mustard, poplar trees, sunflowers, Indian grass can detoxify heavy metals like zinc, copper, nickel, cadmium, degrade petroleum-based hydrocarbons, and can detoxify pesticides and herbicides, etc. [23].
c. *Phytovolatilization:* It involves removal of contaminants from soil or water and their release into atmosphere in less toxic form. Black locust, canola, Indian mustard, alfalfa, poplar trees, ferns grasses are used for this process [23, 24].
d. *Phytostabilization:* It involves use of metal resistant plants for the immobilization of heavy metals. Poplars can volatilize trichloroethylene, meadow grasses can immobilize radioactive plants [23, 39].
e. *Rhizodegradation:* It involves increasing microbial activity in the soil to break organic contaminants. It can be used for the decontamination of sludge due to petroleum oil [40].

Carbon Sequestration and Nanotechnology

Carbon sequestration is a process in which carbon dioxide is captured from the atmosphere and is converted to solid or liquid carbon dioxide, and this carbon dioxide is beneficial for the growth of plants. As a part of natural carbon cycle Plants can sequester carbon through photosynthesis, which stores carbon in the soil as soil organic carbon (SOC). There are different types of carbon sequestration: biological, chemical, geological, and technological [14]. Nanoparticles are widely being used nowadays in carbon sequestration process. This process briefly involves the following steps:

Pre-combustion: Fossil fuels like natural gas or coal are reacted with steam and oxygen to produce a gas mixture called *syngas*, which is mostly made up of CO_2, hydrogen (H_2), and carbon monoxide (CO) [41].

Gasification: The *syngas* is then subjected to a chemical process called gasification, which turns it into hydrogen and CO_2 [42].

Separation: The CO_2 is separated from the exhaust stream using various absorption or adsorption technologies [43].

Storage: The captured CO_2 is stored in deep geological formations or in the form of mineral carbonates [43].

Nanoparticles include both organic and inorganic materials. Carbon nanotubes and graphene nanoparticles are used in carbon capturing technologies. Carbon-based nanoparticles exhibit unique properties which facilitate carbon sequestration. Good surface to volume ratio, adsorption properties make nanoparticles to play pivotal role in CO_2 capturing process and thus helping in combating climate change.

Benefits of Carbon Sequestration

1. It reduces greenhouse gas emissions as carbon dioxide is one of the main greenhouse gases, capturing it and using it as plant fertilizer is beneficial for both plants as well as environment.
2. Another main advantage is that it helps in the restoration of soil and improves the health of the soil in general.
3. It controls air pollution by capturing CO_2 from the atmosphere.

4. It reduces soil erosion, increases agricultural productivity, and thus helps to reduce advent of floods to an extent.
5. It helps in protecting the natural resources, and is a highly beneficial for farmers economically.

Nanoparticles in Green Chemistry

Nanoparticles are the particles which have size between 1 and 100 nm in diameter. Nanoparticles have been synthesized through various green methods. Green nanotechnology, which involves synthesis of nanoparticles of various metals synthesized through green methods, has wide applications in the field of photocatalysis. It has been observed in the research that nanoparticles synthesized using biological methods are more active than those synthesized by chemically fabricated methods [11, 12]. They can be used for the decontamination of environmental pollutants like dyes, antibiotics, pesticides, herbicides etc. and in this manner water pollution can be curbed effectively.

These particles have a well reported photocatalytic activity. Nanoparticles have metal defects like, vacancy defects, interstitial and substitutional defects [44]. Due to these defects, various catalytic processes are affected. Photocatalysis is one of the specific features of nanoparticles. In photocatalysis electron is shifted from filled valence band to the conduction band as a result of absorption of light energy in the form of a photon, as a result a hole is created in the valence band [20]. Dye degradation is carried out on the surface of catalyst by reactive oxygen species formed as a result of reaction of oxygen with electrons in the conduction band [45].

Industrial Development, Safety, and Nanotechnology

Nanotechnology has improved, modernized, made economically viable, commercialized, growth of the industries [7] and has contributed in sustainable development. A brief review of a few major industrial sectors has been summarized below:

a. *Information technology (IT) and electronics industrial sector*: In IT and electronics sector, transistors of nanoscale have been produced and thus entire memory of computer can be stored in one small chip [7].
b. *Petroleum industry:* Nanoparticles are highly efficient catalysts and are used in petroleum industry for petroleum refining [7] and in automobile industries as catalytic converters in automobiles [7], thus contributing in preventing air pollution.
c. *Cosmetic industry:* They are used as nano size emulsions for various skin care products as their penetration efficiency is more. World-famous cosmetic industries are using nanoscale ingredients of chemicals like TiO_2, ZnO, carbon black, silica [8, 9] and some biodegradable nanoparticles [8, 9] in their cosmetics.
d. *Agriculture industry:* In a country like India, where 70% of the population is rural and relies on agriculture, nanotechnology can be of great help and can lead to an industrial revolution. With the advent of climate change, agriculture has been affected severely, so techniques like carbon sequestration when amalgamated with nanotechnology can be highly beneficial. Moreover, nanotechnology introduced in agricultural techniques can lead to better absorption of nutrients by plants [4]. Herbicides, pesticides, fungicides, weedicides have been modified through nanotechnology for better applications in agriculture [4].
e. *Food industry:* In food industry, especially in packaged food nanotechnology is used to check the microbial activity [46]. Nanoscale ingredients have been introduced to enhance the color, texture and flavor of the food [46]. TiO_2, SiO_2, silica, based nanoparticles are used as food additives and ZnO-, MgO-based nanoparticles are used in packaging [47]. They are used in health supplements, for food storage, to increase absorption and preservation of food respectively [47].
f. *Healthcare industry:* Nanotechnology-based diagnostics in MRI (magnetic resonance imaging) and CT (computed tomography) are being developed to enhance the efficiency of these techniques [48]. Efficacy of drugs has been enhanced in pharmaceutical industries by use of nanoscience and their toxicity has been reduced [48].
g. *Manufacturing industry:* There have been two approaches in the manufacturing industry regarding nanotechnology, top-down and bottom-up approaches, the former approach involves

breaking down larger materials to nanoscale by various physical and chemical processes while the latter approach involves combination of compounds or molecules to form nanoscale elements [49]. Carbon nanotubes are manufactured by bottom-up approach are used in water purification, drug delivery, bullet proof vests, components of space ship [49] etc. Diamond nanomaterials are manufactured by top-down approach [49].

Limitations Regarding Industrial Safety

Since nanoparticles are widely used in the industrial field, their safety needs to be accessed. We need to have safe handling of the nanoparticles. It has been reported that prolonged exposure to carbon nanotube–based nanoparticles can cause cancer and respiratory diseases [50]. Due to the nanoscale size, they can easily enter blood stream, brain, and even placenta. They can enter cell mitochondria and their harmful characteristics are enhanced by their high reactivity [50]. They can cause toxicity due to their ability to form reactive oxygen species (ROS). When there is lack of balance between formation of ROS and anti-oxidants, oxidative stress arises in the cells [51], which leads to cytotoxicity.

According to NIOSH (National Institute for Occupational Safety and Health) which is US Government's federal agency for occupational safety, nanomaterials can be highly combustible and can lead to explosions and fire [52]. Nanoparticles embedded in a matrix or in suspended form are least hazardous [52]. Proper storage of nanomaterials is needed and appropriate lab clothing to minimize the dermal contact is needed. Nanotoxicology, an area in which harmful, toxic effects of nanomaterials [51] are accessed and studied should be more researched so that we could know the features these particles which lead to adverse effects and one could work upon eliminating those features.

Potential Disadvantages of Nanoparticles to the Environment

There are some potential risks associated with nanoparticles. Since they are of nanoscale in size, it is difficult to access the scale of pollution due to them, though the risk associated with them is less. Another thing which cannot be ignored is their (nanoparticles') potential risk to health, especially as they can be inhaled easily due to their nanoscale size and can lead to lung diseases [29]. So, cytotoxicity of these particles should be accessed before bringing them into use.

CONCLUSION

Industrialization cannot be compromised by a nation if it needs to be developed, but we cannot compromise with our environment also. So, sustainable development in every field especially in industry is the need of the hour. Nanotechnology has limitless possibilities and due to this it is drawing a lot of attention, but green chemistry amalgamated with nanotechnology is required as it can help in addressing the issue of climate change by reducing the elimination of hazardous substances into the environment and thus preventing pollution, and it can be a good business venture too. Green synthetic routes should be devised and used for synthesis. Green nanotechnology should be promoted and used for industrialization. Industrial safety, while dealing with nanoparticles, should also be accessed and nanotoxicology should be more researched upon. Use of personal protective equipment (PPE), N95 or N100 respiratory filters, safety glasses, face shields should be used in industrial units and labs where nanoparticles are dealt with. Furthermore, use of safety alarms within nano production area center should be promoted so that their release due to accident or malfunction can be curbed [51]. Phytoremediation and carbon sequestration are some of the techniques, which when combined with nanotechnology, can be of immense importance in protecting environment as well as for sustainable development. The need is to identify the right scenarios for achieving developmental and industrial goals.

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