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Environmental Nanotechnological Applications for Sustainable Agriculture

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Agriculture and society are intertwined. Agriculture is necessary for human survival and social sustainability in India. Eco-friendly agriculture practices nurture ecosystems to solve current societal issues. Indian ecosystems are marred by pollution, imbalance, climate changes, food crisis, various diseases, and malnourishment continue as a major concern. The traditional environmental remedial strategies appear relatively ineffective in the ever-expanding use of pollutants that pervade the water, air, and soil environment. Nanotechnology provides an efficient, environmental friendly, and cost-effective solutions to the global sustainability challenges that society is facing. Nanotechnology utilizes nanomaterials that have remarkable physical and chemical features to make smart functional materials for developing sustainable technologies. Nanotechnology seems to be very promising in sustainable environment development, sustainable agriculture, renewable and economically energy alternative through use of nanomaterials for detection, prevention, and removing pollutants. The development of nanotechnology in India has huge potential to address the challenges like providing drinking water, healthcare, nano-based industry, and sustainable agriculture. This review highlights the recent nanotechnology applications to meet the global challenges in providing clean energy technology, water purification, and greenhouse gases management. In addition, effort has been made to analyse the opportunities and limitations in engineered nanomaterials safety, solid waste management, reducing pollution of air water and soil.

Keywords: Environmental nanotechnology, Nanomaterials, Nanotoxicology, Sustainable environment

Introduction

Sustainable agriculture is the method to implement farming techniques that protect ecosystems, environment, and human health, and simultaneously produce adequate amount of agriculture products for social welfare[1]. Population growth and rapidly changing lifestyle are causing environmental implications such as increasing solid waste, air pollution, and contamination of surface and ground water across the world. The major environmental challenges of 21st century are global warming, water and air pollution, and reduced energy supplies. Nanotechnology, a novel branch of science of dealing with the design, synthesis, characterization, and application of nano molecules could help in dealing with the pernicious effects of these challenges on the environment. Nanomaterials display significant physico-chemical assets that make them predominantly smart functional materials for creating sustainable technologies. Nanomaterials exhibit much larger and more reactive surface area when compared to bulk material which can be easily functionalized with the help of several chemical moieties that enhance their affinity toward a given molecule even in gases and dissolved solutes. The surface functionalization helps them to selectively target the key biochemical components and facilitate metabolic pathways as well as signalling networks of water-borne viruses and bacteria. Nanomaterials provide extraordinary opportunities to improve the activity of functional nanomaterials as they exhibit improved optical, electronic, magnetic, and catalytic properties. These innovative functional materials can be administered into numerous forms such as water-soluble particles, supramolecular hosts, particles, membranes, and fibres. In the past decade, this field of science has gained global attention and there has been an exponential increase in the global market of nanoparticle-based products with the market value expected to exceed $3 trillion by the end of the decade. Indian innovators and industries too developing nano-based products which will make our country a global leader in this area. It has applications in diverse fields including medicine, energy production, textiles, food production, sustainable agriculture and packaging, electronics, cosmetics, bioremediation *etc*.

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In addition to the above-mentioned challenges, changing weather patterns has also ledto significant loss of agricultural productivity and food security challenges. Moreover, unsystematic, and enhanced use of chemical fertilizers in agricultural practices without realizing their terrible environmental repercussions is leading to health issues at alarming rate. Researchers working in the fields of soil, air, and water remediation are extremely concerned and are concentrating their efforts on developing strategies, actions, and appropriate measures to reduce the usage of these chemical fertilizers. Globally, food production and distribution are under immense strain owing to the expanding population, climate change, pollution, and augmented water and energy demands[2]. Recently, environmental nanotechnology is emerging as a novel tool which has influenced every sphere of life and provides key solutions to environmental challenges using nanomaterials. It holds the capability to revolutionize the agricultural practices with unique tools for molecular treatment of diseases, prompt detection of disease and augmenting plant's ability for nutrient absorption thereby enhancing the agricultural output. Nanotechnology will not only reinforce the grasp of agribusiness over global food but would also improve the farming practices at every stage ranging from providing the food to hungry and protection of environment thus providing the consumers with better alternatives. Nano-agriculture would take the industrial food chain a step farther by allowing nanoscale genetic manipulation of genetically modified plants. Similarly, nano-pesticides can be designed to eliminate specific undesirable pests. With the use of nanosensors, nano-delivery systems, and low-cost labour, vision of an automated agriculture can now be realized. Creating a bioeconomy is a difficult and complicated process requiring the amalgamation of several disciplines of science[3]. Therefore, this novel branch of nanoscience may have significant impact on making the agriculture more sustainable with the early diagnosis of plant-disease, use of nanofertilizers, nanopesticides, nanosensors for plant health and pest monitoring, and nano-enabled remediation of contaminated soil and water[4-8] (Fig. 1). The large-scale statistical analysis has also revealed the need for alternative economical sources of energy,posing the issue as a global concern.

It is good that the exceptional physicochemical properties of these nanomaterials are gaining attention, but the scientific community needs to look at the safety and sustainability of this new technology.

Fig. 1 — The role of environmental nanotechnology in different sectors

There is no suspicion that nanotechnology will continue to assist scientific tools for the benefit of the environment, but choosing the correct nanomaterial is the key for the successful direction of this technology for its future endeavours. The challenge to the usage of nanotechnology lies in the ability of the research community to understand available environmental and health risks involved with the use of nanomaterials. To provide a regulatory framework it is imperative to understand the toxicity cycle of nanomaterials from production till disposal. Recent interventions has led to development of the new branch of science called nanotoxicology which evaluates the fate, behaviour, prospective interactions and effect of engineered nanomaterials on the environment and health. It also attempts to invite proactive strategic planning for their safe use.

The recent advancements in the nanotechnological applications to ameliorate the global challenges in providing clean and efficient energy technologies, water purification, materials supply as well as utilization, green technology and greenhouse gases management. In addition, the key applications of nanotechnology for the benefit of the environment andthe major grey areas in the field of nanotechnology along with the future perspectives are highlighted. Environmental nanotechnology seems to be very promising in sustainable environment development through use of nanomaterials for detection, prevention, and removing pollutants. In addition, designing industrial processes and production of eco-friendly products using environmental nanotechnology have impacted. Nearly all spheres of life has come under the influence of environmental nanotechnology, as it appears to have solutions for nearly all the environmental problems. The hazards and safety of life are the key bottlenecks of using environmental nanotechnology, as the nanomaterials utilized may stay suspended in the air for a long period, posing the risk of build-up, easy absorption, and damage to living beings. This review is an effort to critically analyse the opportunities and limitations of environmental nanotechnology in solid waste management, controlling and reducing air, water and soil pollution and engineered nanomaterials safety.

Positive implications of nanomaterials

Nanotechnology has the potential to provide economic, social, and environmental advantages. Environmental nanotechnology has a significant impact on many aspects of environmental challenges, from identifying the root causes to develop new remedies. Nanotechnology could lessen human impact on the environment by offering solutions for energy consumption, pollution, and green gas emissions[9]. It proposes the potential for significant environmental benefits that include cleaner, more efficient industrial processes; enhanced ability to detect and eliminate pollution to enhance air, water, and soil quality; reduction of waste by high precision manufacturing; efficient and non-polluting power sources like solar cells;elimination of greenhouse gases and other pollutants from atmosphere;diminished necessity for large industrial plants and remediation of environmental impairments.

Nanomaterials for sustainable environment

Carbon capture, an alternative to combat global warming

In general, much of the energy used in industry is created by burning of fossil fuels, thus releasing significant volumes of carbon dioxide into the atmosphere which would further contribute to the global climate change issue[10]. Amongst the variety of CO_2 capture methods (absorption, adsorption, cryogenics, and membranes) investigated, adsorption regeneration technology is the well documented and established process[11-12]. Previously, adsorbents like activated carbon, zeolites, and silica adsorbents were employed. However, owing to their unique qualities like excellent thermal and chemical stability, adsorbents such as functionalized single-walled carbon nanotubes (CNTs) and multiwalled CNTs have recently garnered interest for CO_2 capture[13-14].

Remediation of Environmental pollutants

Recently, nanotechnology has been explored to provide state of the art technologies for encountering major environmental concerns in a sustainable way. Global warming, environmental pollution, and depleting energy resources are the most critical environmental concerns confronting the earth today[5]. Environmental nanotechnology growing popularity and relevance for pollution reduction, prevention, and restoration of environment involves two approaches *viz*., cleaning up the environment and detecting contaminants.

Nanotechnology can help in reducing the pollution *via* better utilization of less hazardous raw materials, by using other renewable energy resources and prevention of contaminants during manufacturing operations. Significant advancements in the field of environmental nanotechnology include better alternatives for environmental sensing, pollution reduction, waste treatment/remediation, and the generation of cost-effective energy sources such as solar and fuel cells[15]. Applications of Nanotechnology for environmental remediation as well as alternate energy sources are briefly reviewed.

Air pollution remediation

The degradation of air quality has become a major environmental threat, and nanomaterials are being used extensively to mitigate the challenge. Advancements in nano research has led to innovative, efficient, affordable methods for remediation of pollutants present in air, water and soil. One such method for elimination of air pollutants is to utilize nano-catalysts with a larger surface area for gaseous reactions. In environmental nanotechnology remediation operations both natural and engineered nanoparticles are being utilized (Fig. 2). Catalysts made from these nanoparticles provides larger surface area for interaction with the reacting chemicals which in turn enhances their efficacy. Nano-catalysts operate by hastening chemical processes that convert toxic vapours emitted by automobiles and industrial facilities into nontoxic gases[16]. Silver nanoclusters utilized as catalysts could drastically minimize the hazardous byproducts produced during the manufacturing process of propylene oxide, a substance being employed for synthesis of everyday items including plastics, paint, detergents, and brake fluid. A nanofiber catalyst composed of manganese

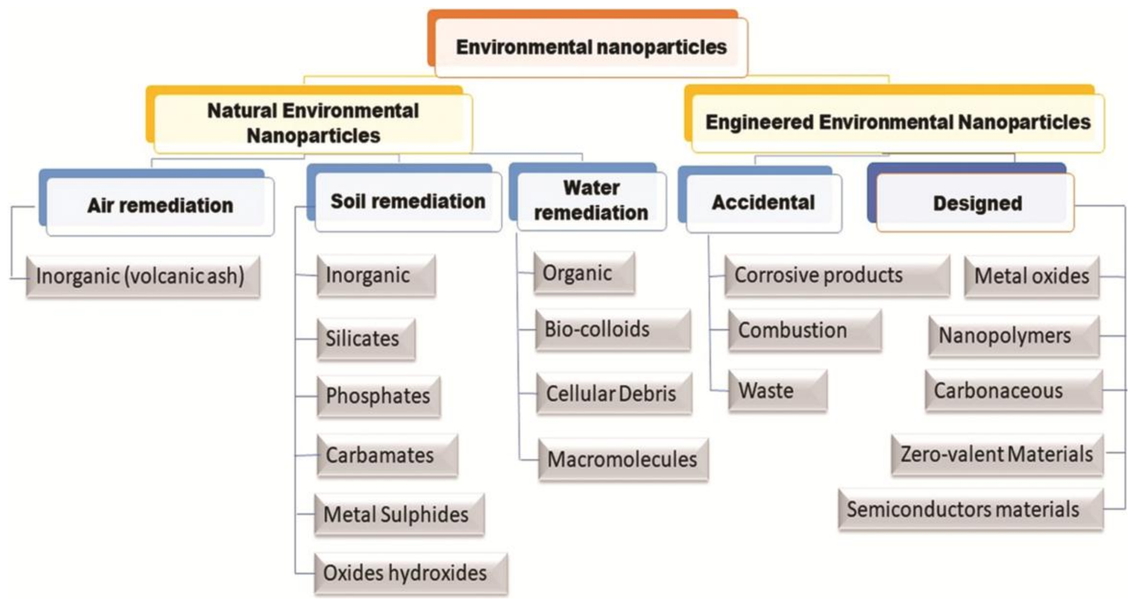

Fig. 2 —Different types of nanoparticles used in environmental nanotechnology

oxide is now in use to remove volatile organic compounds produced from industrial smokestacks. Additionally, investigations are being carried out to enhance the performance of catalysts that could assist in minimizing the impact of air pollution from industrial plants, cars, air conditioners into harmless gasses[15].

Another approach involves the use of nanostructured membranes with tiny pores to sequester methane or carbon dioxide from exhaust. Interestingly, it has been reported that carbon nanotubes (CNTs) could trap gases up to hundred times more efficiently than the previous technologies, allowing them to being employed for large-scale industrial processes and power plants. Unlike traditional membranes, this novel technology could successfully process as well as separate vast quantities of gases. It was discovered in 2006 that it was possible to gather soot filtered out of diesel fuel emissions and recycle it into CNTs manufacturing material[17]. The diesel soot is utilized to synthesize a single walled CNTs filter using laser vaporization, so that the filtered waste effectively becomes the filter itself. Similarly, nanosized catalysts and nanostructure membranes are efficiently utilized to minimize air pollution. Membranes coated with nanomaterials like Graphene Oxide are extensively employed for filtration of pollutants from the air.

Remediation of soil contaminants

Recently, nanotechnology is being used for remediation of soil. Zero valent iron nanoparticles (nZVI) are coming up as a promising solution for the eradication of polluted soils, particularly for removal of polychlorinated biphenyls[15]. Previously, conventional approaches like incineration, landfill disposal, thermal desorption, solvent extraction, and soil washing were employed as soil remediation technologies. However, despite their wide usage, these physicochemical remedial technologies like incineration and landfill disposal remains disruptive and unsustainable. To tackle the issues concerning the restricted mobility of nanoparticles, nZVI created by reducing ferric chloride solution with sodium borohydride were used for in-situ transformation and eventual eradication of the pollutants from soil[18].

Organo-phosphorous pesticides are used as an insecticide on fruits and vegetables and are of great environmental concern, primarily because of their toxicity to mammals and birds[15,19]. Reports have shown that iron nanoparticles (1-10 μg^{-1}) have been engaged for restoration of Organo-phosphorous pesticides contaminated soil. Malathion was found in the soil after leaching into the water with a pH of 8.2 and then oxidised with a small excess of N-bromosuccinimide (NBS). The unutilized NBS was calculated by monitoring the decline in rhodamine B colour intensity[19]. The Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy was used to monitor the degradation product generated during the oxidation of Malathion by nZVI.

Water contamination remediation

Nanotechnology, a revolutionary technique has been employed for water purification since 1990s.

The technology is being used in detection as well as treatment of hazardous contaminants/impurities in water[4,20]. A major issue is the removal of industrial waste pollutants and cleaning solvents (trichloroethylene) which accumulates in river and groundwater. Nanoparticles can catalyse and detoxify trichloroethene, a hazardous contaminant often encountered in industrial effluent. Through chemical reactions, hazardous contaminants in water could be transformed into non-toxic compounds. Gillham for the first time employed ZVI in permeable reactive barriers (PRB), based on his experience with the use of zero valence iron in the purification of waters containing halogenated pollutants[21]. The application of zero-valent iron (ZVI or Fe0) for in-situ remedial treatment has been extended to encompass diverse pollutants. To allow remediation of various organic and inorganic groundwater contaminants it is suggested that nanomaterials should be efficient as hydro-dehalogenation and reduction catalysts[22]. ZVI have been utilized for in redox reactions for reduction of chromium to Cr (III) and Pb to Pb (0) thus allowing reduction of aqueous contaminants. Iron nanoparticles have the potential of cleaning up organic solvents that pollute the groundwater by spreading over the water body and decomposing the organic solvent[15].

Further, semi-permeable membranes have been used in traditional water filtration systems via electrodialysis or reverse osmosis. Reducing the membrane pore size to nanometer range would enhance the selectivity of molecules permitted to flow through. Recently, researchers have developed a thin film membrane with nanopores that can efficiently desalinate water. Membranes capable of filtering viruses are already accessible[23]. Ion exchange nanoresins, which are organic polymer substrates with nano-sized pores on the surface where ions are trapped and exchanged for other ions, are also commonly employed in separation, purification, and decontamination of water. These resins are generally employed in water softening and purification. Moreover, unique nanoparticles on filtration membranes could convert the contaminating chemicals into harmless product thus improving the quality of water. Nanotechnology has proven to be highly effective in reaching contaminants dispersed in underground ponds and is cheaper than methods which require pumping the water out of the ground for treatment. The technique of deionization exploiting nano-sized fibre as an electrode is not only less expensive, but also highly energy efficient[18].

Nano-fertilizers for enhanced productivity

Massive rise in crop productivity over the last few decades has played a vital role in satisfying the world's nutritional requirements. This surplus productivity is the result of the increased usage of chemical fertilizers. However, these chemical fertilizers have lesser usage efficiency owing to their volatilization and leaching, ultimately leading to environmental pollution and higher production cost. This issue has raised concern in scientific community to find a better and sustainable alternative to enhance the nutrient availability to crops. To our surprise, nanotechnology has been successfully utilized to decrease mobile nutrient losses, produce slow-release fertilizers, and increase the availability of nutrients that are generally not readily absorbed. Nanofertilizers include the nanomaterials which either act as nutrients or carriers/encapsulating agent for improving the nutrients accessibility[3]. Contrary to conventional fertilizers these nanofertilizers are cost effective, allows better nutrient uptake via nanometric pores, and enhance the plant metabolism thereby contributing to agricultural sustainability. Studies have shown that in soybeans, use of phosphatic nanofertilizers has led to a 32% increase in growth rate and 20% rise in seed production in comparison with traditional fertilizers[24]. Moreover, nano-enabled fertilizers also facilitate controlled and slow release of nutrients as and when needed by plants thus limiting the conversion of surplus fertilizers to volatile forms or preventing their leakage in environment[25]. Clay minerals, hydroxyapatite, chitosan, polyacrylic acid, zeolite, and other nanostructured materials are utilized to create fertilizers nano formulations for soil or foliar applications. Nano Urea developed by nano formulations is liquid fertilizer given to plants by foliar spray. Through stomata and other opening urea enter in to plants distributed via phloem as per requirement, additional nitrogen gets assimilated in vacuoles and is released gradually. The additional advantage of nano fertilizers are an efficient delivery mechanism which is missing in other biofertilizers.

Nano-pesticides and nanobiosensors

Fabrication of novel, efficient, and target-specific pesticides is a constant process which in turn has major implications on the food chain (in pesticides, vaccines, veterinary medicine, and nutritionally enhanced food), and human health[2]. Excessive and non-targeted use of pesticides has led to expansion of pesticide resistance in weeds, insects, and pathogens.

Although biopesticides tend to lessen the toxic effects of synthetic pesticides, however their application is limited due to their slow and environment-dependent efficacy against pests. Interestingly, nanopesticides have the potential to circumvent these constraints by improving the pesticide efficiency, agricultural production and by reducing the input costs through waste and labour reduction. Development of smart nanosensors and nanopesticides delivery systems with enhanced effectiveness and requirement in lower dosages, will aid the agriculture industry to combat viruses and pests. Nanopesticides owing to their slow degradation and regulated release of active components may provide a long-term pest control thus providing an effective and sustainable method to reduce the usage of synthetic chemicals causing environmental hazards. To boost their efficacy, nanopesticides act differently than traditional pesticides[25]. Therefore, usage of nanopesticides in less quantities and less frequently than traditional pesticides also help in saving water and energy. However, ecotoxicological aspect and risk assessment of these nanopesticides should also be considered to ensure their sustainable usage in agriculture. Studies have shown the effectiveness of several types of nanopesticide formulations on a wide range of pests. Silver, copper, and aluminium are examples of key inorganic nanoparticles with pesticidal characteristics. Moreover, it has been observed that polyethylene glycol-based nanoformulations of carbofuran and acephate as well as permethrin as nano formulations was found to be more effective against the pests than their commercial counterpart[3].

Nanotechnological applications are already being explored to increase the soil fertility and crop yield. Amalgamation of biotechnology and nanotechnology as sensors would result in more sensitive equipment, allowing earlier reaction to environmental changes[2]. As described below, nano-sensors have recently been introduced to monitor environmental health.

- Carbon nanotube or nano cantilever nanosensors are tiny enough to capture and quantify individual proteins or even small molecules.
- Other nanosensors function by initiating an enzymatic response or by employing nanoengineered branching molecules called dendrimers as probes to bind to target chemicals and proteins.
- Engineered nanoparticles or nanosurfaces can be used to initiate an electrical or chemical signal in the presence of a contaminant, such as bacteria.
- Precision farming, with the use of smart sensors, will eventually allow increased agricultural output by delivering precise information, thereby allowing farmers to make better decisions.

Nanotechnology as renewable & economical energy alternative

Global energy consumption is rising as the world's population and economy is expanding. Energy production from traditional sources such as fossil and mineral fuels has now increased the environmental effect owing to quicker depletion of fossil fuels. It is predicted that global energy consumption would rise by 44% between 2006 and 2030[26]. As a result, the utilization of renewable energy sources for sustainable and green energy production has lately received global attention[27]. Bioenergy, geothermal energy, hydropower, ocean energy, solar energy, and wind energy are all examples of renewable energy sources. Nanotechnology has immensely augmented the alternative energy resources in order to greet the burgeoning global energy demands. Innovations in this area has led to reduced consumption of energy and shrinkage of toxicity burden on environment. Enhancing the energy efficiency, sustainable energy production, energy conversion, energy storage, and energy saving are the various approaches employed in environment nanotechnology[5].

Nanotechnology for efficient energy conversion

Employment of nanotechnology could be done to generate green energy via manufacture of solar and fuel cells, which are commercially viable alternative for clean energy sources.

Solar cells

Solar cells, also known as photovoltaic cells, convert the solar energy into electrical energy and are comprised of a semiconducting material silicon. These traditional solar cells have low efficiency (14%) and significant production costs. Even though solar energy is abundant, photovoltaic technology accounts for just 0.04 % of the world's total fundamental energy supply[28]. First-generation solar cells which continue to dominate the market were mostly built on silicon wafers have performance efficiency of 15-20% only[29]. Further, thin film technology was used to create the second-generation cells, which employ amorphous silicon, cadmium telluride, and copper indium gallium diselenide.

Although there was a large cost reduction however, owing to technological issues and stability their efficiency (10-15%) remains even lower than the first generation[30]. Recently, third-generation solar cells which are still in its infancy, have been designed using nanocrystals and nanoporous materials, and these may prove to be more promising alternative. Solar cells may be classified into three varieties based on nanotechnology: dye-sensitized solar cells, hybrid organic solar cells, and quantum dot solar cells. In these solar cells, light energy conversion and capture are achieved by modifying a nanostructured semiconductor capture interface with a dye, conjugate polymer, or semiconductor nanocrystal, respectively.

Fuel cells

A fuel cell is a device that transforms chemical energy from a fuel into electrical energy via an electrochemical reaction between a hydrogen-containing fuel with oxygen or another oxidizing agent[31]. The fuel cell market has expanded quickly in recent years and these cells may be utilized for a variety of purposes, including transportation power, portable power generation, and stationary power generation. A fuel cell could carry on a variety of fuels, including hydrogen, methanol, and ethanol. Furthermore, if hydrogen is utilized for fuel cells, there will be no carbon gas emissions. When compared to other energy conversion devices, fuel cells feature minimal emissions, great efficiency, and portability. Nonetheless, high capital costs and short lifetimes are some of the drawbacks of fuel cells[5].

It is interesting to note that recent nanotechnology research has produced several promising nanomaterials and efficient membranes which could make fuel cells cheaper, lighter, more efficient, and long lasting.Further, the cost of catalysts used in fuel cells for generating hydrogen ions from fuels like methanol is reduced by intervention of nanotechnology. Previous investigations have shown that modified carbon nanotubes (doped with nitrogen or coated with an electron-drawing polymer polydiallyldimethylammonium chloride) may exhibit better nanocatalytic activity and are capable of replacing the widely used platinum in fuel cells. It has been observed that the power output of a fuel cell utilising carbon nanotube electrodes is better than their platinum counterpart. Moreover, unlike platinum, their catalytic activity is not harmed by carbon monoxide when utilising methanol as a fuel, which further increases the cell's lifetime[32]. Further research has shown use of a nanoporous Metal-Organic-Framework (MOF) to store gases such as hydrogen or methane.

Nanotechnology for storage of energy

Efficient energy storage systems are also required in addition to sustainable energy generation which employs renewable energy technologies. Some of the potential electrical energy storage systems that use nanotechnology, such as rechargeable batteries and supercapacitors, are discussed here.

Rechargeable batteries

High energy rechargeable lithium-ion batteries have a wide range of uses in consumer electronics, portable power devices, and electric vehicles[33]. Even though lithium-ion batteries have captured > 82% of the small portable market in a few years, there are still certain issues like greater costs, toxicity, and the charging voltage which is too high (for lithium cobalt oxide) and dangerous for electric cars. As a result, nanostructures are being developed to improve power performance and battery specific energy by creating new electrode materials and electrolyte solutions.

To improve safety, graphite anodes can be replaced with nanostructured materials such as nanowires, nanorods, and nanoporous materials. Si nanowires, Ge nanowires, and carbon-coated silicon nanowire array films are examples of recent advancements in ultrahigh capacity anode materials[34,35]. Furthermore, Si graphene composite electrodes for lithium-ion batteries perform better, while tin nanoparticles coated with carbon integrated with graphene perform better in terms of cycle performance and conductivity[36]. CNTs are also widely used as an electrode material in rechargeable Li-ion batteries[37,38]. Similarly, nanostructuring the cathode improves energy storage and charge cycle stability, and nanomaterials such as $LiCoO_2$, $LiFePO_4$, $LiMn_2O_4$, and $LiMn_2O_4$ are often utilized[39]. Furthermore, the addition of metal oxide NPs to polymer electrolyte, such as SiO_2, TiO_2, $Al_2 O_3$, ZrO_2, Sn_2O_3, and $LiAlO_2$, increases its performance[40].

Employment of nanotechnology as energy saver

One of the most important methods to satisfy our future energy demands is by saving energy. By using inorganic and organic semiconductor materials, nanotechnology can give new approaches to boost the efficiency of energy usage.

Thermal insulation

Aerogels are nanostructured extremely porous materials with exceptional thermal insulation qualities. They have a wide range of applications in homes and commercial facilities, including oil pipelines and space mission[41]. Super thermal insulation is a term used to describe silica aerogel with low thermal conductivity, which is frequently employed in the building industry[5]. Nanocarbon aerogels with high energy storage capacity are employed as electrode materials in supercapacitors, which include hydrogen storage[42].

LED and OLED lighting

The light-emitting diode (LED) is one of the potential lighting sources that is now being researched intensively, and it is theoretically more energy efficient than fluorescent bulbs. To achieve high efficiency and good rendering capabilities, a semiconductor material utilized in LED applications must have high crystallinity as well as an adjustable band gap. Because of their crystal clarity and adjustable emission, semiconductor nanostructures such as Quantum dots are widely researched for the creation of light-emitting materials[43]. Various nanostructures are available for energy saving applications. Their increased efficiencies have been attributed to heat flow impedance caused by phonon scattering at the interfaces of nanomaterials[5].

Grey areas in nanotechnology

Nanomaterials have exceptional qualities, and its products can assist the environment and the economy, yet nano composites may potentially degrade the environment in many other ways. Environmental consequences and hazards related to nanotechnology are poorly understood and inconsistently assessed[9]. The following are some of the potential environmental consequences of nanotechnology:

- High energy requirements for nanoparticle synthesis, leading to high energy demand
- Diffusion of toxic nanosubstance's causing environmental harm
- Lower recovery and recycling rates of nanomaterials
- Lack of environmental implications and risk assessment of nanoparticles
- A lack of trained engineers and workers, causing additional concerns.

Despite several advancements in the field of nanotechnology, synthesis of safe and desirable nanomaterials for their sustainable applications is not yet attained. These limitations have surfaced owing to the certain challenges in the field of environmental nanotechnology[44]. A brief account of these issues is discussed below.

Discrepancy amid the activity, selectivity, and stability of nanoparticles

The strong reactivity of the surface and microstructure results in excellent performance by enhancing the adsorptive or catalytic efficiency of engineered nanoparticles (ENPs) for environmental applications. The property of selective adsorption or degradation is also imperative for addressing certain environmental challenges. Furthermore, the severe and hazardous circumstances typical in environmental applications would readily decrease the nanocatalytic composition and stability, a major indicator of sustainability of nanoparticles. Contrary to the utilization of ENPs in chemical and energy sector, stability of nanoparticles is critically important in biomedical and environmental applications as leaching of metal from metal-based nano catalysts or generated intermediates may lead to formation of secondary contaminants[45]. Therefore, activity, selectivity, and stability of nanoparticles should be considered for rational design of nanomaterials and management of their applications.

Lack of systematic analyses/mechanistic studies

Along with their superior performance in the novel field of environmental applications, nanomaterials also trigger a variety of processes involving distinct mechanisms[46] (Fig. 3, Table 1). The composition of the materials can also influence the competitive adsorption or catalytic activity of nanoparticles. Thus, the specificity and uniqueness of these novel working methods is dependent on the diverse physicochemical properties of nanomaterials including their shape, size, composition, surface attributes and hybridizations. For efficient utilization of environmental nanotechnology, it is essential to explore both, the environmental processes and materials science of nanoparticles. This could be efficiently done *via* amalgamation of traditional quenching experiments with *in situ* spectroscopy and computational investigations for mechanistic studies of nanomaterials. To bring theoretical results to actual environmental applications of nanomaterials, chemical engineering efforts may be of great usage.

Nanopollution and nanobiointeractions, the major concerns

Nanotechnology and nanomaterials have led to a wide range of biological applications, such as sensing, diagnosis, and healing, which would have been

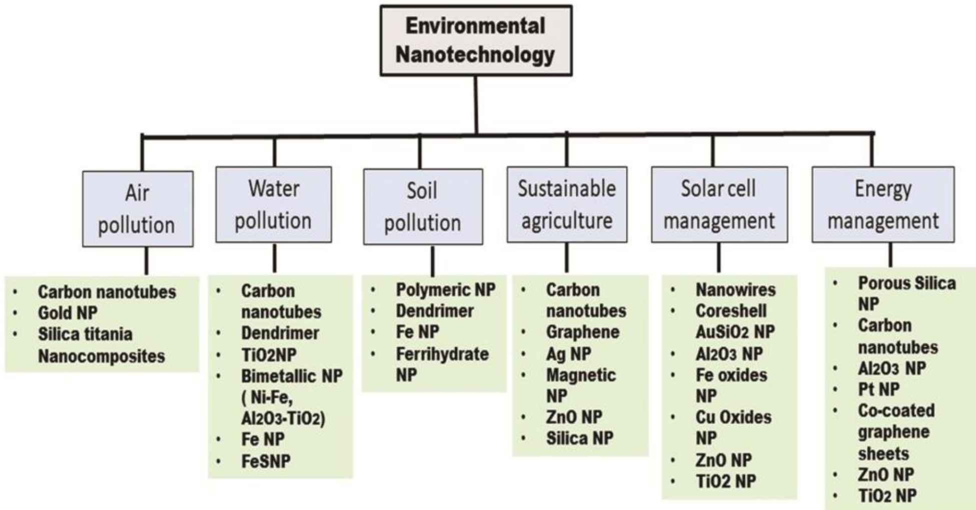

Fig. 3 — Application of environmental nanomaterials in environmental remediations, monitoring and management

Table 1 — Role of different nanomaterials for environmental remediation

S. No.	Application	Nanomaterial	Target Pollutant
1.	Water remediation	Carbon nanotubes	Absorption of Zn (II) and Fluoride from water
		Iron	Removal of nitrate from water
		Iron sulphide	Degradation of lindane from drinking water
		Bimetallic Iron/Palladium	Dechlorination of chlorinated ground water
		Titanium dioxide	Degradation of Butachlor and dye in aqueous solution;
		PAMAM dendrimers	Wastewater - Heavy metals
		Polymer nanocomposites	Water - Metal ions, dyes, microorganisms
		Iron NPs	Removal of Pb, Cr ions
		Titanium dioxide	Photocatalysis of water polluted from dyeing and printing process
2.	Air and Soil remediation	Titanium dioxide	Removal of benzene and toluene; Photodecomposition of phenol
		Zirconium and Niobium-doped titanium oxide	Photoinduced decomposition of acetone
		Silica	Biosafe insecticide
		Titanium dioxide/PVDF membrane	Oxidization of nitrobenzene
		Microporous metalorganic framework	Trapping of aromatic compounds
		Bimetallic Palladium-gold	Dechlorination of Trichloroethylene (TCE)
		Bimetallic nickel-iron	Dechlorination of Trichloroethylene (TCE)
		Silica-titania nanocomposite	Mercury vapor removal
		Amine-modified PDLLA-PEG	Gaseous-Volatile organic compounds
		Polyamine-modified Cellulose	Gaseous-Volatile organic compounds
		Amphiphilic polyurethane NPs	Soil-Polynuclear aromatic hydrocarbons
		Carbon nanotubes	Adsorption of Pb^{2+}, Cu^{2+}, and Cb^{2+} ions
		Iron NPs	Nickel sequestration in water
3.	Renewable energy source (Solar energy)	Iron NPs	Arsenic removal
		Zinc oxide	Improved photovoltaic performance of solar cells Photovoltaic cell
		Zinc oxide	Solar cell
		Core-shell gold-silica	Plasmon-enhanced light absorption in solar cell
		Silica	Thermal insulation
		Gold thin film	Conversion of CO to CO_2
		Platinum nanoparticle	Fuel cells
		Carbon nanotube	Fuel cells
		Graphene	Efficient solar cells

Impossible to achieve using their counterpart bulk materials. However, the repercussions of these applications could be fate and transport human and environmental exposure, as well as toxicity or health hazards to human bodies. Therefore, in most of the circumstances, emergence of nanomaterials is visualized as two sides of a coin where both opportunity and difficulty has arisen together[47]. Nanopollution is no longer a point of contention, but rather a serious threat. Concisely, basic knowledge, identification, and manipulation of nano-bio interactions are therefore the primary concerns of environmental nanotechnology.

Lack of proper guidelines and knowledge on nanotoxicity

Industry and education sectors will have to adapt to the shift in the labour dynamics/composition to adapt to the changes in societal developments pertaining to science, technology, and engineering fields[48]. A crucial component in minimizing the negative effects of nanotechnology is to have a systematized training programme for laboratories. Another major concern is that researchers working in nanotechnology do not completely comprehend how nanoparticles could influence a system, which is due to the lack of specific guidelines on toxicity and safe disposal of nanoparticles. Therefore, accessibility of toxicity information from the manufacturer, may simply lead to safe handling of nanoparticles using suitable safety equipment[9,48]. Furthermore, inclusion of general nanosafety courses in educational institutes and organizing nano safety seminars/conference could educate/benefit the scientists working in fields which contains nanomaterials.

Ecotoxicity of nanomaterials

Nano formulations have been used for environmental clean-up at a burgeoning pace. There are several classic examples where nanotechnology can be used for positive effects on the environment including remediation of environmental degradation, increasing the sources of renewable energy and many more. Apart from these positive effects of nanotechnology on the environment, there are several examples to showcase negative effects of nanomaterials on the environment[49-50]. It is of prime importance to understand the resulting damage to the environment against the cost of using them for the benefit of the environment. Therefore, it is vital that nanomaterials used for the benefit of the environment should be critically and rightly chosen after proper ecotoxicity measurement to have a huge impact on the environment.

Potential environmental effects

These nanomaterials can act as environmental contaminants and have the potential to act as environmental stressors affecting terrestrial and aquatic ecosystems[51] and impacting ecological organization. Bioaccumulation of nanomaterials and their toxic effects have reported environmental burdens by many authors[52-55]. Several authors have also reported trophic transfer and accumulation of nanomaterials in terrestrial species[56-59]. Massive deposition of nanoparticles can also occur because of changes in pH, ion concentration and stabilizing agents[60]. The interactions of nanomaterial with other components of the environment also affect their toxicity properties. They may act as carriers and transport toxic materials with them. These nanomaterials are also known to affect the mobility, sequestration and degradation of known harmful compounds like heavy metals[61]. Nanomaterials are also known to alter the behaviour in wildlife and humans[62].

Complexity of ecotoxicity measurements

The chemical structure of nanomaterials is very critical in toxicity measurements. The major problem in the toxicity analysis is that even a slight change in the chemical structure of nanomaterials will drastically change its properties. Another interesting issue related to the ecotoxicity of nanomaterials is nanoparticle cell interaction and nanoparticle metabolism in cells. It is well known that nanomaterials can pass through barriers of trophic levels, therefore, ecotoxicity measurements should be performed in test systems at different trophic levels from primary producers to secondary consumers in their natural habitats at all the stages. This will help to check biomagnification of nanomaterials in the food chain as organisms at specific test levels perform specific ecological functions. The protocols for risk assessment should be standardized for specific physiological conditions like modes of exposure, duration of exposure and functional levels of test systems. Life-cycle risk assessment should be included in the toxicity measurement to include the risks involved during transport, transformation and recycling of nanomaterials. An upstanding experimental design is therefore essential to reduce the risk involved due to the life-cycle of nanomaterials. Many of the nanoparticles are soluble in water and tend to harm the environment as it is nearly impossible to separate them from water. This low /no recovery of nanoparticles is causing further environmental implications. In spite of the mounting evidence that behavioural data is not used in the regulatory studies, recent reports have also suggested that these contaminants can also affect the behaviour of wildlife and humans[62]. Understanding the behavioural patterns should also be included in the toxicity measurements. Continued scientific input is required to analyse the nanoparticle fate, behaviour, effect, life-cycle risk assessment so that nanoparticles can be precautionarily used with minimum negative effect and are sustainable in the long-term.

Methods of ecotoxicity measurement

Though this field of nanotoxicology is complex and focuses on the inherent hazards of nanomaterials, diverse scientific groups have recently teamed up to create robust, reliable and accurate set of tools for detection and measurement of particle size specific data. Number of researchers have embarked on a mission to understand possible mechanisms of nanoparticle toxicity[63]. Various possible nanotoxicology assays have been described in detail so far. Steps have already been taken and it is well documented that nanomaterials can cause reactive oxygen species production during toxicity causing oxidative stress. *In vitro* methods to study the toxicity of nanomaterials include experiments determining oxidative stress, cell viability, cell uptake and transport, DNA damage, proliferation assay, inflammatory changes, apoptosis assay[64,65]. *In vivo* nanotoxicity tests have been performed in *Arabidopsis thaliana*[66], *Daphnia magna*[67], *Caenorhabditis elegans*[68], and *Drosophila melanogaster*[69] and small rodents. Various advanced techniques like Atomic Force Microscopy (AFM), Biomimetic 3-D Lung-on-a-Chip, Carbon Fiber Microelectrodes (CFMEs), Fluidic-Based Cell-on-Chip (CoC), High-Throughput Nanotoxicity Screening, Lateral Flow Immunoassay (LFIA), Organ-on-Chip,Precision-Cut Tissue Slices can be used to assess nanotoxicity at the level of excellence[69]. A lot of work has been done to assess nanotoxicity but still our knowledge base to interpret toxicity data is insufficient.Hence more studies are required to assess nanotoxicity of nanomaterials and fill in our knowledge gaps[70]. Recently nanoinformatics has strived as a major overhaul leading to phenomenal outcomes[71]. It provides computational approaches for functional discoveries of nanotoxicology assessment and data management and helps to expand our toolbox for the same. Innovative methods for ecotoxicity measurement are required to protect environment and human health.

Conclusion

Nanotechnology has tremendous potential which is not yet fully explored. It is pertinent to include safe designing of nanomaterials, toxicity testing using model organism, ecological impacts of engineered nanoparticles andtheir risk assessments. Nanotechnology has immense potential in agriculture fields, including nano-agrochemicals, nanofertilizers, nanopesticides, water management, wastewater treatment, natural disaster management, drug delivery, diagnosis, with nanotubes, plant genetics, disease prevention, (*e.g*. nanobiotic-Ag), aquaculture and fishery, nutraceuticals, drug delivery breeding of farm animals, *etc*. In the recent years, severe consequences of nanotechnology have been observed in different environmental segments contributing to contamination of soil, air, and water. Owing to their larger surface area, chemical manufacturing processes and increased toxicological pollution, engineered nanoparticles may cause more damage to the environment than the bulk particles. However, in depth knowledge of the environmental effects and risks of nanotechnology is still restricted and unpredictable. Therefore, despite the wide applicability of environmental nanotechnology, rational designing and better exploitation of nanomaterials is the need of the hour. Currently, fate of nanoparticle in the environment remains unknown due to a crucial lack of baseline data. Pertinent research on these lines will undoubtedly encourage efficient utilization of nanotechnology while alleviating negative environmental impacts.

References

1 Tilman D & Clark M, Global diets link environmental sustainability and human health. *Nature*, 515 (2014) 518.

2 Kuykendall T, Ulrich P, Aloni S & Yang P, Complete composition tunability of InGaN nanowires using a combinatorial approach. *Nat Mater*, 6 (2007) 951.

3 Manjunatha SB, Biradar DP & Aladakatti YR, Nanotechnology and its applications in agriculture: A review. *Int J Farm Sci*, 29 (2016) 1.

4 Sharma B & Deswal R, Single pot synthesized gold nanoparticles using *Hippophae rhamnoides* leaf and berry extract showed shape-dependent differential nanobiotechnological applications. *Artif Cells Nanomed Biotechnol*, 46 (2018) 408.

5 Pathakoti K, Manubolu M & Hwang HM, Nanotechnology applications for environmental industry in Micro and Nano

Technologies. In: *Handbook of nanomaterials for industrial applications*, (Ed by C.M. Hussain; Elsevier) 2018, 894.
6 Kumar K, Dangi K & Verma A, Efficient & eco-friendly smart nano-pesticides: Emerging prospects for agriculture. *Mater Today: Proc*, 45 (2021) 3819.
7 Mittal D, Biswas L & Verma A, Redox resetting of cisplatin-resistant ovarian cancer cells by cisplatin-encapsulated nanostructured lipid carriers. *Nanomed,* 16 (2021) 979.
8 Yadav M, Niveria K, Sen T, Roy I & Verma A, Targeting nonapoptotic pathways with functionalized nanoparticles for cancer therapy: Current and future perspectives. *Nanomed,* 16 (2021) 1049.
9 Zhang B, Misak H, Dhanasekaran PS, Kalla D, & Asmatulu R, Environmental impacts of nanotechnology and its products. In: *Proceedings of the Midwest Section Conference of the American Society for Engineering Education*. 2011, 1.
10 Keith DW, Why capture CO_2 from the atmosphere? *Science*, 325 (2009) 1654.
11 White CM, Strazisar BR, Granite EJ, Hoffman JS & Pennline HW, Separation and capture of CO_2 from large stationary sources and sequestration in geological formations—coalbeds and deep saline aquifers. *J Air Waste Manag Assoc*, 53 (2003) 645.
12 Rao AB & Rubin ES, A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control. *Environ Sci Technol*, 36 (2002) 4467.
13 Lu C, Bai H, Wu B, Su F & Hwang JF, Comparative study of CO_2 capture by carbon nanotubes, activated carbons, and zeolites. *Energy Fuels,* 22 (2008) 3050.
14 Hsu SC, Lu C, Su F, Zeng W & Chen W, Thermodynamics and regeneration studies of CO_2 adsorption on multiwalled carbon nanotubes. *Chem Eng Sci*, 65 (2010) 1354.
15 Sulaiman MB &Santuraki AH, Applications and Implications of Environmental Nanotechnology. In: *Research Trends in Environmental Science* (AkiNik Publications Delhi) 2018, 53.
16 Pandey B & Fulekar MH, Nanotechnology: Remediation Technologies to clean up the Environmental pollutants. *Res J Chem Sci*, 2 (2012) 90.
17 Uchida T, Ichihara M, Tamura T, Ohtsuka M, Otomo T & Nagata Y, Full color pixel with vertical stack of individual red, green, and blue transparent organic light-emitting devices based on dye-dispersed poly (N-vinylcarbazole). *Jpn J Appl Phys*, 45 (2006) 7126.
18 Agarwal S, Al-Abed SR & Dionysiou DD, *In situ* technologies for reclamation of PCB-contaminated sediments: current challenges and research thrust areas. *J Environ Eng,* 133 (2007) 1075.
19 Singhal RK, Gangadhar B, Basu H, Manisha V, Naidu GRK & Reddy AVR, Remediation of malathion contaminated soil using zero valent iron nano-particles. *Am J Anal Chem,* 3 (2012) 76.
20 Sarvestani MRJ & Doroudi Z, Removal of reactive black 5 from waste waters by adsorption: a comprehensive review. *J water Environ Nanotechnol*, 5 (2020) 180.
21 Gillham RW, *In situ* treatment of groundwater: Metal-enhanced degradation of chlorinated organic contaminants. *Advances in groundwater pollution control and remediation* (Springer, Dordrecht) 1996, 249.
22 Ponder SM, Darab JG & Mallouk TE, Remediation of Cr (VI) and Pb (II) aqueous solutions using supported, nanoscale zero-valent iron. *Environ Sci Technol,* 34 (2000) 2564.
23 Tepper F & Kaledin L, Virus and protein separation using nano alumina fiber media. http://www.argonide.com/ Paper%20PREP%2007-final .pdf. 2009.
24 Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, Ur Rehman H, Ashraf I & Sanaullah M, Nanotechnology in agriculture: Current status, challenges and future opportunities. *Sci Total Environ,* 721 (2020) 137778.
25 Liu R & Lal R, Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (*Glycine max*). *Sci Rep*, 4 (2014)56.
26 Khan NA, Khan SU, Ahmed S, Farooqi IH, Dhingra A, Hussain A & Changani F, Applications of nanotechnology in water and wastewater treatment: a review. *Asian J water Environ Pollut,* 16 (2019) 81.
27 Khan J & Arsalan MH, Solar power technologies for sustainable electricity generation - A review. *Renew Sustain Energy Rev*, 55 (2016) 414.
28 Prakash R & Bhat IK. Energy, economics and environmental impacts of renewable energy systems. *Renew Sustain Energy Rev*, 13 (2009) 2716.
29 Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N & Gorini R, The role of renewable energy in the global energy transformation. *Energy Strategy Rev*, 24 (2019) 38.
30 Parida B, Iniyan S & Goic R, A review of solar photovoltaic technologies. *Renew Sustain Energy Rev*, 15 (2011) 1625.
31 Hermann AM, Polycrystalline thin-film solar cells–a review. *Sol Energy Mater Sol Cell*s, 55 (1998) 75.
32 Andújar JM & Segura F, Fuel cells: History and updating. A walk along two centuries. *Renew Sustain Energy Rev*, 13 (2009) 2309.
33 Gong K, Du F, Xia Z, Durstock M & Dai L, Nitrogen-doped carbon nanotube arrays with high electrocatalytic activity for oxygen reduction. *Science,* 323 (2009) 760.
34 Kang K, Meng YS, Breger J, Grey CP & Ceder G, Electrodes with high power and high capacity for rechargeable lithium batteries. *Science,* 311 (2006) 977.
35 Chan CK, Zhang XF & Cui Y, High capacity Li ion battery anodes using Ge nanowires. *Nano letters*, 8 (2008) 307.
36 Huang R, Fan X, Shen W & Zhu J, Carbon-coated silicon nanowire array films for high-performance lithium-ion battery anodes. *Appl Phys Lett*, 95 (2009) 133119.
37 Liang S, Zhu X, Lian P, Yang W & Wang H, Superior cycle performance of Sn@C/grapheme nanocomposite as an anode material for lithium-ion batteries. *J Solid State Chem*, 184 (2011) 1400.
38 Centi G & Perathoner S, Carbon nanotubes for sustainable energy applications. *Chem Sus Chem*, 4 (2011) 913.
39 Gwon H, Hong J, Kim H, Seo DH, Jeon S & Kang K, Recent progress on flexible lithium rechargeable batteries. *Energy Environ Sci*, 7 (2014) 538.
40 Bazito FF & Torresi RM, Cathodes for lithium ion batteries: the benefits of using nanostructured materials. *J Braz Chem Soc*, 17 (2006) 627.
41 Liu W, Lin D, Sun J, Zhou G & Cui Y, Improved lithium ionic conductivity in composite polymer electrolytes with oxide-ion conducting nanowires. *ACS Nano*, 10 (2016) 11407.
42 Ivanov GR, Tomova R, Djambova ST, Nadoliiski M & Dimova-Malinovska D, Functionalized aerogels–new

nanomaterials for energy-efficient building in Preliminary AFM, Nanoidentation and EIS studies. *J Phys Conf Ser* (IOP Publishing) 253 (2010) 012077.

43 Zuo L, Zhang Y, Zhang L, Miao YE, Fan W & Liu T, Polymer/carbon-based hybrid aerogels: preparation, properties, and applications. *Materials*, 8 (2015) 6806.

44 Kah M, Tufenkji N &White JC, Nano-enabled strategies to enhance crop nutrition and protection. *Nat nanotechnol*, 14 (2019) 532.

45 Sun H, Grand Challenges in Environmental Nanotechnology. *Front* Nanotechnol, 1 (2019) 2.

46 Saputra E, Muhammad S, Sun H, Ang HM, Tade MO & Wang S, Different crystallographic one-dimensional MnO_2 nanomaterials and their superior performance in catalytic phenol degradation. *Environment Sci Technol*, 47 (2013) 5882.

47 Duan X, Sun H & Wang S, Metal-free carbocatalysis in advanced oxidation reactions. *Acc Chem Res*, 51(2018) 678.

48 HochellaJr MF, Mogk DW, Ranville J, Allen IC, Luther GW, Marr LC, McGrail BP, Murayama M, Qafoku NP, Rosso KM & Sahai N, Natural, incidental, and engineered nanomaterials and their impacts on the Earth system. *Science*, 363 (2019) 6434.

49 Asmatulu R & Asmatulu E, Importance of recycling education: a curriculum development at WSU. *J Mater Cycles Waste Manag*, 13 (2011)131.

50 Rana S & Kalaichelvan PT, Ecotoxicity of nanoparticles. *ISRN Toxicol*, (2013) 574648.

51 Klaine SJ, Koelmans AA, Horne N, Carley S, Handy RD, Kapustka L, Nowack B & von der Kammer F, Paradigms to assess the environmental impact of manufactured nanomaterials. *Environ Toxicol Chem*, 31 (2012) 3.

52 Lead JR, Batley GE, Alvarez PJJ, Croteau MN, Handy RD, McLaughlin MJ, Judy JD & Schirmer K, Nanomaterials in the environment: behavior, fate, bioavailability, and effects-An updated review. *Environ Toxicol Chem*, 37 (2018) 2029.

53 Unrine JM, Tsyusko OV, Hunyadi SE, Judy JD & Bertsch PM, Effects of particle size on chemical speciation and bioavailability of copper to earthworms (*Eisenia fetida*) exposed to copper nanoparticles. *J Environ Qual*, 39 (2010) 1942.

54 Shoults-Wilson A, Reinsch BC, Tsyusko OV, Bertsch PM, Lowry GV & Unrine JM, Role of particle size and soil type in toxicity of silver nanoparticles to earthworms. *Soil Sci Soc Am J*, 75 (2011) 365.

55 Feng Y, Cui X, He S, Dong G, Chen M, Wang J & Lin X, The role of metal nanoparticles in influencing arbuscular mycorrhizal fungi effects on plant growth. *Environ Sci Technol*, 47 (2013) 9496.

56 Zhao L, Sun Y, Hernandez-Viezcas JA, Hong J, Majumar S, Niu G, Duarte-Gardea M, Peralta-Videa JR & Gardea-Torresday JL, Monitoring the environmental effects of CeO_2 and ZnO nanoparticles through the life cycle of corn plants an *in situ* μ-XRF mapping of nutrients in kernels. *Environ Sci Technol*, 49 (2015) 2921.

57 Judy JD, Unrine JM &Bertsch PM, Evidence for biomagnification of gold nanoparticles within a terrestrial food chain. *Environ Sci Technol*, 45 (2011) 776.

58 Hawthorne J, De la Torre Roche R, Xing B, Newman LA, Ma X, Majumdar S, Gardea-Torresdey J & White JC, Particle-size dependent accumulation and trophic transfer of cerium oxide through a terrestrial food chain. *Environ Sci Technol*, 48 (2014) 13102.

59 Majumdar S, Trujillo-Reyes J, Hernandez-Viezcas JA, White JC, Peralta-Videa JR & Gardea-Torresdey JL, Cerium biomagnification in a terrestrial food chain: Influence of particle size and growth stage. *Environ Sci Technol*, 50 (2016) 6782.

60 Maharramov AM, Hasanova UA, Suleymanova IA, Osmanova GE & Hajiyeva NE, The engineered nanoparticles in food chain: potential toxicity and effects. *SN Appl Sci*, 1 (2019) 1362.

61 Guzman KAD, Finnegan MP & Banfield JF, Influence of Surface Potential on Aggregation and Transport of Titania Nanoparticles. *Environ Sci Technol*, 40 (2007) 7688.

62 Joner EJ, Hartnik T & Amundsen CE, Environmental fate and ecotoxicity of engineered nanoparticles. In*: Norwegian Pollution Control Authority Report no. TA 2304/2007*. Ås, (Norway: Bioforsk), 2008, 1.

63 Lochab A, Gadre SD & Saxena R, Green electrochemical sensors based on ionic liquid nanocomposites for detection of environmental pollutants. *Indian J Biochem Biophys*, 59 (2022) 387.

64 Ford AT, Ågerstrand M, Brooks BW, Allen J, Bertram MG, Brodin T, Dang Z, Duquesne S, Sahm R, Hoffmann F, Hollert H, Jacob S, Klüver N, Lazorchak JM, Ledesma M, Melvin SD, Mohr S, Padilla S, Pyle GG, Scholz S, Saaristo M, Smit E, Steevens JA, Van Den Berg S, Werner K, Wong BBM, Ziegler M & Maack G, The role of behavioral ecotoxicology in environmental protection. *Environ Sci Technol*, 55 (2021) 5620.

65 Savage DT, Hilt JZ & Dziubla TD, *In vitro* methods for assessing nanoparticle toxicity in Nanotoxicity. In*: Methods in Molecular Biology*, (Ed by Zhang Q, Humana Press: New York, NY, USA) 2019, 1.

66 Shinde RB, Veerapandian M, Kaushik A & Manickam P, State-of-art bio-assay systems and electrochemical approaches for nanotoxicity assessment. *Front Bioeng Biotechnol*, 8 (2020) 325.

67 Zielińska A, Costa B, Ferreira MV, Miguéis D, Louros JMS, Durazzo A Lucarini M, Eder P, Chaud MV, Morsink M, Willemen N, Severino P, Santini A & Souto EB, Nanotoxicology and nanosafety: Safety-by-design and testing at a glance. *Int J Environ Health Res*, 17 (2020) 4657.

68 Charão MF, Souto C, Brucker N, Barth A, Jornada DS, Fagundez D, Ávila DS, Eifler-Lima VL, Guterres SS, Pohlmann AR & Garcia SC, *Caenorhabditis elegans* as an alternative *in vivo* model to determine oral uptake, nanotoxicity, and efficacy of melatonin-loaded lipid-core nanocapsules on paraquat damage. *Int J Nanomed*, 10 (2015) 5093.

69 Ong C, Yung LYL, Cai Y, Bay BH & Baeg GH, *Drosophila melanogaster* as a model organism to study nanotoxicity. *Nanotoxicol*, 9 (2015) 396.

70 Leudjo TA, Tata CM, Klink MJ, Mbianda XY, Mtunzi FM, & Naidoo EB, A Review on Conventional and Advanced Methods for Nanotoxicology Evaluation of Engineered Nanomaterials. *Molecules*, 26 (2021) 6536.

71 Bidgoli SA, Endocrine Disrupting Effects of Carbon Nanotubes: A Systematic Review on Next Generation Nanotechnology based Agrochemicals. *J Water Environ Nanotechnol*, 5 (2020) 102.

72 Checker VG, Sharma B & Kathpalia R, Nanoinformatics – A newly introduced tool for research. *Indian J Biochem Biophys*, 59 (2022) 431.