Sustainable Plant Nutrition in a Changing World

Vishnu D. Rajput
Krishan K. Verma
Neetu Sharma
Tatiana Minkina *Editors*

The Role of Nanoparticles in Plant Nutrition under Soil Pollution

Nanoscience in Nutrient Use Efficiency

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Preface

Nanotechnology, with its research and outcomes, has become one of the most important fields in the forefront of all disciplines of sciences. The promising results of research hold great potential for providing breakthroughs that will revolutionize the scientific progresses in all fields. *The Role of Nanoparticles in Plant Nutrition Under Soil Pollution* presents a comprehensive review of the role of nanotechnology in agriculture in a compilation of 16 chapters related to importance, recycling, and transformation of nanoparticles, role of nanotechnology in increasing yield and growth, and nanoparticles as bioremediation agents. Each chapter provides a detailed perspective of principle, procedure, glitches, and solutions of diverse topics with illustrative work in the form of figures and tables for students, researchers, and professionals. The purpose of this book is to provide a brief introduction to the application of nanotechnology in the field of agriculture that allows students, academicians, and researchers to obtain insights into the developments in this area. The topics include the global importance, bioavailability and transformation process, interaction with soil pollutants and their impact on soil systems, use of nanoelements in combating plant nutrition, and biofortification. The other important areas covered include nano-biosensors, interaction of nanoparticles with plant hormones, and impact of nanoparticles on genetic makeup of the plant system along with risks and concerns of their usage in agriculture. This book includes recent research and innovations along with case studies that will help readers grasp the updated content in a better way.

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Nanning, China — Krishan K. Verma
Punjab, India — Neetu Sharma
Rostov-on-Don, Russia — Tatiana Minkina

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About the Editors

Vishnu D. Rajput is working as an associate professor (leading researcher) at Sothern Federal University, Russia. His ongoing research is based on soil contaminations, that is, potentially toxic elements, and metallic nanoparticles, and investigating the bioaccumulation, bio/geo-transformations, uptake, translocation, and toxic effects of metallic nanoparticles on plant physiology, morphology, anatomy, the ultrastructure of cellular and subcellular organelles, cytomorphometric modifications, and DNA damage. He comprehensively detailed the state of research in environmental science in regard to how nanoparticles/heavy metals interact with plants, soil, microbial community, and the larger environment. He has published (total of 290 scientific publications) 167 peer-reviewed highly rated full-length articles, 15 books, 60 chapters (Scopus indexed), and 37 conference articles and achieve h-index: 18 by Scopus with 1320 citations, till April 2022. He is an internationally recognized reviewer (peer reviewed 180 manuscripts and has received an outstanding reviewing certificate from Elsevier, Springer and Plants-MDPI. He is an editorial board member of various high-impact journals. Dr. Rajput has received “Certificate for Appreciation” 2019, 2021; “Certificate of Honor 2020” and Diploma Award 2021 by Southern Federal University, Russia, for “Outstanding Contribution in Academic, Creative Research, and Publication activities”. He has also received “Highly qualified Specialist” status by Russin Govt. https://www.researchgate.net/profile/Vishnu-Rajput; https://www.scopus.com/authid/detail.uri?authorId=56516545100

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Tatiana Minkina is the head of Soil Science and Land Evaluation Department at Southern Federal University. She is the head of international master’s degree educational program “Management and estimation of land resources” (2015–2022, accreditation by ACQUIN). Her area of scientific interest is soil science, biogeochemistry of trace elements, environmental soil chemistry, soil monitoring, assessment, modeling, and remediation using physicochemical treatment methods. She was awarded in 2021 with Diploma of the Ministry of Education and Science of the Russian Federation for many years of long-term work for development and improvement of the educational process and significant contribution to the training of highly qualified specialists. Currently, she is handling projects funded by the

Russian Scientific Foundation, Ministry of Education and Science of the Russian Federation, and Russian Foundation of Basic Research. She is a member of the Expert Group of Russian Academy of Science, the International Committee on Contamination Land, Eurasian Soil Science Societies, the International Committee on Protection of the Environment, and the International Scientific Committee of the International Conferences on Biogeochemistry of Trace Elements. Her total scientific publications are as follows: 957 (total 957, 389 in English); Scopus—268, WoS—196, and citing index: Scopus—1976, h-index—21; WoS—1452, h-index—20. She is the invited editor of an open access journal from MDPI, *Water* (ISSN 2073-4441; impact factor: 3.229; SJR 0.718), and editorial board member of *Geochemistry: Environment, Exploration*, *Analysis* (ISSN: 1467-7873; impact factor: 1.545; SJR: 0.346), and the *Eurasian Journal of Soil Science* (e-ISSN: 2147–4249; SJR 0.24). https://www.researchgate.net/profile/Tatiana-Minkina; https://www.scopus.com/authid/detail.uri?authorId=15063165400

Chapter 1
Global Importance and Cycling of Nanoparticles

Uzma Kafeel, Urfi Jahan, Fariha Raghib, and Fareed Ahmad Khan

1 Introduction

A nanoparticle is a matter particle between 1 and 100 nanometers (nm) in diameter. At times the word is intended for bigger particles, up to 500 nm, or fibers and tubes that are smaller than 100 nm in only two directions (Vert et al. 2012). Nanoparticles are distinguishable because their infinitesimal size derives very diverse physical or chemical properties, like colloidal properties, optical or electrical properties. Nanoparticles are produced both naturally or synthesized as engineered materials. Naturally occurring nanoparticles (NNPs) are made through cosmological, geological, meteorological, and biological ways (Simakov et al. 2015; Simakov 2018). Engineered nanoparticles (ENPs) are produced as pure particles or composites and in several shapes and sizes and surface structures which are additionally conjugated to different bioactive molecules, forming an estimable number of variants with indefinite potential for biological uses (Ha et al. 2013), including better procedures for decreasing pollution, water management, environmental sensing, bioremediation, and making alternate energy resources more economical. The exceptional characteristics of nanoparticles facilitate these innovative technologies to encounter environmental tasks with a viable approach (Pathakoti et al. 2018). Given the mounting prominence of nanoparticles in research and developmental activities, risks associated with health, safety, and the environment should be highly considered. Accordingly, rules for safe handling, usage, and disposal of nanoparticles should be provided and strictly monitored in research and occupational sites to lessen the threats from health, safety, and environmental exposures. The chapter

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broadly centers on the environmental applications of nanoparticles and emphasizes their safe disposal and cycling.

2 Global Importance of Nanoparticles

2.1 Soil Remediation

In the present decade (2021–2030), which is declared as the UN decade for Ecosystem restoration, the remediation of soil systems is of utmost concern (Rajput et al. 2021). Improper management of metropolitan and industrial waste, unrestrained and laid-back chemical discharge, commonly due to industrial activity, and too much treatment of pesticides and fertilizers in crop production lead to soil deterioration. In current times, soil pollution is of grave concern, and the need to conserve soil quality is pivotal for ecosystems and human health (Galdames et al. 2020). Heavy metal (HM) pollution is alarming, owing to their toxicity, non-biodegradability, and accumulation (Naikoo et al. 2020). HMs hinder various physiological processes comprising disruption of cell functions, modifications in enzyme specificity, damaging cell membrane and DNA configuration (Bruins et al. 2004; Naikoo et al. 2019a; Raghib et al. 2020). Some plants accumulate and endure high levels of HMs due to their proficient biochemical tolerance mechanisms which makes them superb contenders for phytoremediation of contaminated soils (Naikoo et al. 2019b). Even though useful, these conventional strategies are time-consuming and costly. Remediation with nanoparticles is considered a favorable approach for the decontamination of HM-contaminated soils (Xue et al. 2018; Fajardo et al. 2019). It is more operative and economical than conventional approaches because of the better reactivity of nanoparticles plus the option of in-situ management.

Three widely used nanoparticles in soil remediation are nanoscale zero-valent iron (nZVI) particles, nanoscale calcium peroxide (CaO_2), and nanoscale metal oxides used for the degradation of halogenated organic compounds, destruction of organics, and adsorption of metals, respectively (Mueller and Nowack. 2010). Fajardo et al. (2019) reported the effectiveness of nanoparticle remediation in soil contaminated with HMs. Chemical analysis showed that adding nZVI stabilized elevated zinc concentrations (Zn) and lead (Pb) used in the study (Carmen et al. 2019). After some weeks of nZVI application, when the bioavailability and toxicity of HMs are reduced, bioremediation can be done subsequently to enhance detoxification and improve the nano remediation strategy's efficiency for restoring contaminated sites. Applications of nZVI particles have attained favorable results, making them predominantly useful for remediation of subsurface contaminants. Degradation of many such deterrent halogenated aliphatic hydrocarbons with nZVI, for example, the degradation mechanism of cis-dichloroethylene (cis-DCE), trichloroethylene (TCE), tetrachloroethylene (PCE), and trans-dichloroethylene (trans-DCE), has been studied and reported (Arnold and Roberts 2000). Bare nZVI particles also reduce nitrate concentrations (Galdames et al. 2020).

Iron nanoparticles (FeNP) showed promising results in remediation of soils contaminated with chlorinated organic compounds, metals (Lowry and Johnson 2004; Zhang 2003), and arsenic (As) (Shipley et al. 2010). Magnetite (Fe_3O_4) and hematite (Fe_2O_3) nanoparticles effectively remove arsenic (As^{3+}), (As^{5+}), cadmium (Cd), chromium (Cr), cobalt (Co), nickel (Ni), selenium (Se), molybdenum (Mo), vanadium (V), lead (Pb), antimony (Sb), thallium (Tl), thorium (Th), and uranium (U) to negligible concentrations, suggesting their budding potential in remediation of HM-contaminated soils (Shipley et al. 2010). CaO_2 nanoparticles act as oxidants in treating soils containing different carbon-based pollutants, such as heating oil, gasoline, ethylene glycol, methyl tertiary butyl ether, and solvents. Also, they are highly effective in removing aromatics and are used in advanced bioremediation. The O_2 released in the reaction of CaO_2 with H_2O helps in forming an aerobic atmosphere backing up natural bioremediation by aerobic organism's existent in soil (Mueller and Nowack 2010).

2.2 *Water Treatment*

Using nanoparticles in water and wastewater treatment has been considered extensively due to their minuscule size and vast specific surface areas. Nanoparticles have remarkable adsorption capacities, high reactivity, and mobility (Khan and Siddiqui 2020a, b). Various nanoparticles have successfully removed bacteria, heavy metals, inorganic anions, and organic contaminants present in water (Tang et al. 2014; Liu et al. 2014; Yan et al. 2015; Kalhapure et al. 2015). Nanomaterials widely used for water and wastewater treatment include carbon nanotubes (CNTs), metal oxide nanoparticles, nanocomposites, and zero-valent metal nanoparticles (Lu et al. 2016). Silver nanoparticles (Ag NPs) are widely used to disinfect water, acting as an excellent antimicrobial agent. Ag NPs stick to the bacterial cell wall, enter it, cause structural modifications in the cell membrane, and increase its permeability (Quang et al. 2013). Among many zero-valent metal nanoparticles, nZVI and nZVZ (nano zero-valent zinc) are better-reducing agents relative to various redox-labile pollutants (Yang et al. 2019).

Despite a weaker reduction potential, Fe possesses many noticeable benefits over Zn among exceptional adsorption properties, oxidation, precipitation, and is cost-effective. nZVI is efficient in eliminating a wide series of contaminants, together with halogenated organic compounds (Liang et al. 2014), nitroaromatic compounds (Xiong et al. 2015), organic dyes (Hoag et al. 2009), phenols (Wang et al. 2013), heavy metals (Galdames et al. 2020), inorganic anions such as phosphates (Markova et al. 2013) and nitrates (Muradova et al. 2016), metalloids and radio elements (Ling and Zhang 2015). CNTs are also likely substitutes for treating wastewater owing to their large surface area, ease of chemical and physical modification, and rapid adsorption kinetics (Lu et al. 2016). They have excellent adsorption effects toward Mn^{7+} (Yadav and Srivastava 2017), Tl^{1+} (Pu et al. 2013), Cu^{2+} (Tang et al. 2012), Pb^{2+} (Kabbashi et al. 2009), and Cr^{6+} (Tuzen and Soylak 2007).

Although each nanoparticle discussed above has its own advantages, their respective disadvantages cannot be ignored. CNTs can only be used with secondary medium or matrix to form structural components as it is difficult for CNTs to suspend evenly in different solvents. Besides, nanoparticles frequently face difficulty in aggregation, oxidation, poor separation, and an extreme pressure drop when cast-off in flow-through systems and fixed-bed (Yunus et al. 2012). To avoid such issues and improve elimination efficiency, nanocomposites are considered an operative strategy for treating water and wastewater (Galdames et al. 2020). Water and wastewater treatment demand safe, continuingly stable, and cheap materials. Research is still ongoing to acquire desired nanocomposites. An in-depth study and understanding mechanisms of the interaction vis-à-vis the hosts and guests of nanocomposites is vital to lead the synthesis of nanocomposites productively.

2.3 Air Pollution Control

Nanomaterials act as potential super adsorbents to confiscate various kinds of organic and inorganic air contaminants. Toxic gases present in ambient air are cleaned through nanoparticles. An example of such usage in harmful gas cleaning is the adsorption by CNTs and gold (Au) particles. CNTs are single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs). SWNTs are chemical sensors for nitrogen dioxide (NO_2) and ammonia (NH_3), and MWNTs are used as hydrogen (H_2) storage (Yunus et al. 2012). CNTs give suggestively better outcomes than activated carbon and aluminum oxide (γ -$Al_2O_{3)}$ in confiscating dioxins (Bhushan 2010), NO_x (Long and Yang 2001), sulfur dioxide (SO_2), and carbon dioxide (CO_2) (White et al. 2003; Aaron and Tsouris 2005). This advancement of CNTs is perhaps attributable to their curved surface equated with flat sheets, which provide more vital interactive forces between pollutants and CNTs (Yunus et al. 2012). In addition to NO_2 and SO_2, there are several atmospheric pollutants, such as nitrous acid (Indarto 2012), polyaromatic compounds (Santiago and Indarto 2008; Indarto et al. 2009), volatile organic compounds (VOCs) (Sinha and Suzuki 2007), and soot (Indarto 2009) that nanoparticles effectively adsorb.

Combination of very porous manganese oxide (MnO) and Au nanoparticles (which are grown in it) at room temperature is beneficial for removing VOCs from the air (Sinha and Suzuki 2007). This accomplishment is due to porous MnO, which has a considerably larger surface area than all earlier known compounds. The presence of Au nanoparticles reduces the barrier of radical formation. This novel combination unlocked the opportunity for further nano-metal compounds. Isopropyl alcohol (IPA) is used in manufacturing semiconductors and optoelectronic devices. Lack of air pollution control causes IPA vapors to be released into the atmosphere without any remediation. These vapors are carcinogenic and cause skin irritations in humans. Hsu and Lu (2007) oxidized SWNTs in a solution of hydrochloric acid (HCl), nitric acid (HNO_3), and sodium hypochlorite (NaClO), which was used to adsorb IPA vapors. After being oxidized by HCl, HNO_3, and NaClO solution, physicochemical properties of SWNTs considerably enhanced, resulting in reduced pore size simultaneously increasing the surface of functional groups, the surface area of micropores, and the dynamic surface of the base. Subsequently, SWNTs adsorb even more IPA vapors from the air stream (Hsu and Lu 2007). Nanowires like Si nanowires (SiNWs) are adept tools for chemical and biological sensors (Smart et al. 2006). Their minuscule dimension and capability to identify several analytes in actual sensors can help detect chemical and biological pathogens in air, water, and food.

2.4 Agriculture and Crop Productivity

In recent years, nanoparticles have played a substantial role in food security, food safety, and global food production using nanoscale micronutrients in exploring the relationship between nutritional status and crop diseases. Besides enhancing crop yield, nanoparticles can exploit the benefits of agriculture means through able products such as pesticides, soil and plant sensors, and disease management (Khan and Siddiqui 2020a, b; Raghib et al. 2020; Khan et al. 2021). Nanoparticles lessen the applied quantity of plant safety products, curtail nutrient damages in fertilization, and upsurge crop harvests through enhanced nutrient management (Predoi et al. 2020). Nanoparticles optimize soils deficient in elements like Fe, Zn, Se, P, Ca, and Mg (Gogos et al. 2012). In recent years, nanoparticles have been used to make several nano-products that are used as fertilizers, for example, active nano-grade organic fine humic [CN 1472176-A] (Yang et al. 2007), oxide nano rare earth [CN1686957-A] (Wang et al. 2011), nanosilver [KR 000265-A] (Jo et al. 2009), and nano-selenium [U.S. 0326153-A] (Li et al. 2012).

Nanofertilizers control the discharge and organization of nutrient fluctuation over time with their uptake, curtailing the loss of nutrients through soil or air (Tarafdar et al. 2014). There is a constructive effect on crop development and pathogen inhibitions relative to Ag, Mg, Si, TiO_2, or ZnO nanoparticles (He et al. 2011; Yin et al. 2011; Jaberzadeh et al. 2013; Delfani et al. 2014; Janmohammadi et al. 2015). Foliar application of ZnO nanofertilizer on Pearl millet enhanced shoot length by 16%, root length by 4.5%, chlorophyll content by 24%, and soluble leaf protein by 38% (Tarafdar et al. 2014). ZnO NPs are also useful in controlling pathogen growth, are less toxic than AgNP sand, and enhance soil fertility. Usage of ZnO NPs resulted in complete disturbance of cell functions of fungi *Botrytis cinerea* and *Penicillium expansum,* distorting hyphae and fungal complexity (He et al. 2011). The antifungal action of AgNPs is described by their amassing in the fungal hyphae, which disrupts cell functions, an extreme mechanism associated with a higher ion discharge on the amplified nanoparticle surface area (Yin 2011). A dose of 50 μg/ml MWCNTs on tomato roots resulted in improved fresh and dry weight and altering gene expressions (Khodakovskaya 2011).

The foliar application and root application of Fe_2O_3 nanoparticles on soybean resulted in root elongation and better photosynthetic parameters (Alidoust and Isoda

2013). Exposure of spinach roots to TiO_2 nanoparticles enhanced growth rate, photosynthetic rate, chlorophyll content, and RuBisCo activity (Linglan et al. 2008). An additionally capable candidate is TiO_2 NPs because of their assembled photocatalytic and antimicrobial activity. Application of TiO_2 NPs suppressed septicity of *Penicillium cubensis* on cucumber by 90% and increased photosynthetic activity by 32% (Cui et al. 2009). The application of cerium oxide (CeO_2) nanoparticles on cucumber leaves exhibited increased leaf-root translocation signifying phloem-based transportation in the plant (Hong 2014). Zn nanoparticles protected rice plants from ROS impairment by improving levels of antioxidant enzyme actions during germination.

Consequently, Zn nanoparticles-treated seeds exhibited more significant potential for germination (Azarin et al. 2022). To achieve higher crop production, the development of varieties for effective nutrient use can supplement agricultural tactics (Al Tawaha et al. 2020). Tomato plants infected with *Phytothphora infestans* tested for the effect of CuO_2 nanoparticles revealed 74% disease suppression and 58% improvement in nutrient quality (Gianoussi et al. 2013). The problem of in-plant translocation is worth mentioning, i.e., the way foliar application of nanoscale nutrients affects root pathogens, is still under study in the sense that pathogens can be released after root to shoot transfer or induced host resistance. Fertilizing nanoparticles' activity is subjective to the physical and chemical features of the surroundings, i.e., soil, air, and water. The original properties of nanoparticles may transform because of interactions with both biotic and abiotic soil constituents. These adaptations may impact the stability of nanoparticles, their availability to plants, and their transport and aggregation.

2.5 Reducing Heavy Metal Contamination

Soil and groundwater pollution by toxic heavy metals (HMs) remains one of the most challenging environmental concerns faced worldwide. Due to the magnitude and potential of the toxication legacy and high contaminant mobility, it is practically not possible to sequester metals from polluted locations cost-effectively. Nanoparticles are applied in situ and become special assistance for deep toxic zones or inaccessible with traditional methods (Carmen et al. 2019). The stabilized nanoparticles commendably hold up leachability and bio-accessibility of HMs in water, soil, and other porous media. Chromium (Cr) has been extensively identified in groundwater and soils. The US Environmental Protection Agency (USEPA) set a maximum pollutant quantity of 0.1 mg/L for total Cr in drinkable water to diminish human exposure as Criswater-soluble and mobile. Conventionally Cr^{6+} is removed from water by reducing it to its less noxious form, Cr^{3+}, following precipitation (Guha and Bhargawa 2005). Researchers have revealed that Fe^{2+} can effectively reduce Cr^{6+}. Reduction of Cr^{6+} to Cr^{3+} by coarse ZVI particles and non-stabilized or amassed ZVI nanoparticles have been examined in labs and field research (Alowitz and Scherer 2002; Blowes et al. 1997; Melitas et al. 2001; Ponder et al. 2000).

Amending CMC-stabilized ZVI nanoparticles in Cr^{6+} laden soil can substantively decrease chromate leachability (Xu and Zhao 2007). Minor quantity of the stabilized nanoparticles diminished the Cr^{6+} leachability, simultaneously converting all leached Cr^{6+} to $Cr^{3+.}$ (Xu and Zhao 2007). Lead (Pb), placed as the second most harmful element according to the ATSDRs Substance Priority List 2019, is a widespread and potentially toxic contaminant. Present-day remediation skills depend mainly on diggings and relatively pricey landfills and are often ecologically troublesome. Liu and Zhao (2007) combined and verified vivianite nanoparticles (a new category of nanoscale iron phosphate) with carboxymethylcellulose (CMC) as a stabilizer. Results showed that CMC-stabilized nanoparticles successfully decrease the TCLP leachability and PBET bioaccessibility of Pb^{2+} in three representative soils (calcareous, neutral, and acidic). The TCLP leachability of Pb^{2+} was reduced by 85–95%, and the bio-accessibility by 30–45%. Adding chloride (Cl) in the treatment further decreased the TCLP leachable Pb^{2+} in soils, suggesting the formation of chloro-pyromorphite minerals. Interaction of ZnO nanoparticles and AM fungi decreased Pb toxicity in wheat by increasing antioxidants and restricting Pb uptake (Raghib et al. 2020).

Using nanoparticles reduces almost 50 percent phosphate discharge in the surroundings (Xu et al. 2014). Xu and Wang (2017) studied different dynamics on graphene oxide (GO) adsorption performance to confiscate heavy metals during batch trials, with pH, a dose of the adsorbent, interaction time, temperature, and existing ions. It was concluded that GO was an effective adsorbent for Zn^{2+}. Zhao et al. (2011) combined multi-layered GO nanosheets and used them to adsorb Cd^{2+} and Co^{2+} in water. Correspondingly, the maximum adsorption capacities of Cd^{2+} and Co^{2+} onto GO were 106 and 68 mg/g. Lisha and Anshup (2009) examined the elimination effect toward Hg^{2+} by using Au nanoparticles sustained on Al. The elimination capacity of Au nanoparticles toward Hg extended up to 4.7 g/g, much greater than common adsorbents. Au nanoparticles were recovered proficiently, signifying that Au nanoparticles sustained on Al can be useful in wastewater treatment.

Application of super-paramagnetic Fe_2O_3 nanoparticles to treat acid mine drainage (AMD) completely removed Al^{3+}, Mg^{2+}, Mn^{2+}, and 80% of Ni^{2+} and Zn^{2+} (Kefeni et al. 2018). Fe_2O_3 nanoparticles are non-toxic, highly stable, and outstanding metal adsorbers, hence a likely candidate to decontaminate wastewater polluted with heavy metals (Yang et al. 2019). In a study, Fe_3O_4 and Fe_2O_3 nanoparticles were detected to eliminate arsenic (As) via column studies. A retardation factor of about 6742 showed high adsorption of As by Fe_3O_4 nanoparticles in the column. High retardation factor, strong adsorption, and impervious desorption suggest that Fe_3O_4 and Fe_2O_3 nanoparticles can be used to remove as through in situ techniques (Shipley et al. 2010).

2.6 *Clean Energy and Environment*

A continuous stock of energy is required to satisfy the rapidly expanding economy. This has posed an enormous burden on the existing energy setup and the environment. The unwarranted depletion of limited fossil fuels tends to desiccate energy resources and causes severe environmental pollution and global warming (Xia et al. 2014). Most developing nations have vast renewable and non-renewable energy resources, yet many are challenged with critical energy problems. Precisely, energy resource in the form of electricity in many of these countries is so low, affecting trade and industrial activities, and further stunts the whole nation's development. Nanoparticles can offer cleaner, more reasonable, effective, and steadfast approaches to harness renewable energy resources. Developing countries could overcome energy supply challenges and head toward energy self-reliance, alongside decreasing dependency on conventional, environment contaminating energy resources. Such concerns have compelled us to strive for next-generation energy sources. Recent signs of progress in research and development to commercialize a huge range of nanomaterials have been groundbreaking. With the expansion and commercialization of nanoparticles, many devices have been developed to produce, store, transfer, and even conserve energy for a sustainable future (Ranjan et al. 2021).

Nanoparticles have appeared as ultimate platforms to resolve energy conversion issues in solar cells and fuel cells, improve energy storage of lithium-ion batteries and supercapacitors and clean the environment as green catalysts, sensors, pollution prevention, and remediation (Xia et al. 2014). Photons move electrons from a material; electrons flow through wires as an electric current. Nanoparticles significantly improve the efficiency of these processes. ZnO nanoparticle, a transparent conductor, is favorable for use in solar energy approaches, including the photocatalytic splitting of H_2O molecules to discharge hydrogen fuel (Pal and Thapa 2019). CNTs, fullerenes, and quantum dots are being used to create lighter solar cells, inexpensive and more effective. The ratio of increased surface area to volume of these materials increases solar emission capturing by uncovering more conducting surfaces to solar radiation (Zhang et al. 2015). Using nano lead selenide results in releasing more electrons and more electricity to be released when hit by a photon of light with external quantum proficiencies exceeding 120% (Davis et al. 2015).

Nanocomposites of cobalt oxide (Co_3O_4) nanoparticles fixed to conducting graphene as a progressive anode material for better performance of lithium (Li) ion batteries revealed longer battery performance through great revocable capacity, admirable cyclic performance, and noble rate competency, emphasizing the prominence of electrochemically active Co_3O_4 nanoparticles and graphene for energy storage in lithium-ion batteries (Wu et al. 2010). CNTs are excellent substitutes for conventional graphite electrodes in batteries. They have a large surface area, better electrical conductivity, and undeviating geometry making them very reachable to battery electrolytes causing amplified electrical output (Amin et al. 2020). CNTs increase the conductivity of electrolytes resulting in increased energy output therefore, more potent, smaller, and light-weight batteries are widely used in a range of applications (Amin et al. 2020). Nanobatteries can recharge about sixty times faster than standard batteries.

Several of these can function over a wide range of temperatures than is currently available (Echiegu 2016), are also used to optimize and improve the wind turbine blades making them durable, longer, and less heavy to enhance the efficiency of wind turbines and the amount of electricity generated. This remarkable innovation allows future wind turbines to harvest ultra-mega sources of clean energy. Besides, CNTs can also be used as sensors to monitor these huge blades (Brahim 2020). Ding et al. (2014) developed nanostructures called PlaCSH (plasmonic cavity with subwavelength hole-array) to intensify the LEDs' brightness, productivity, and clearness. These amplified the yield of light abstraction to 60%, which is 57% greater than normal LEDs, simultaneously increasing the clarity by 400%. Higher illumination also dismisses the heating problem triggered by the light confined in normal LEDs. Plasmonic cavities can achieve these results because of nano size, metallic structures can control light in such a way those large materials or non-metallic nanostructures cannot. Nanomaterials have made geothermal energy more hands-on by leasing effectual energy production nearer to the surface and at low temperatures. The heat-retaining characteristics of the fluid are improved with nanoparticles. Adding nanoparticles to the fluid increases its capacity to preserve heat, improving efficiency and profitability (Ahmadi et al. 2019).

3 Global Production and Cycling of Nanoparticles

Nanoparticles are a major part of the material flows in the global economy. A report by Allied Market Research expectantly shows the nanomaterial market to grow above $55 billion by the year 2022 (Fig. 1.1) from $15 billion in 2015, growing at a compound annual growth rate (CAGR) of 21% during this period. The USA is expected to keep the leading position until the year 2022, with the nanomaterials market proceeds budding at a rate of 19%. Among Asian countries, China and India are estimated to be the quickest growing nanomaterial markets; however, China is

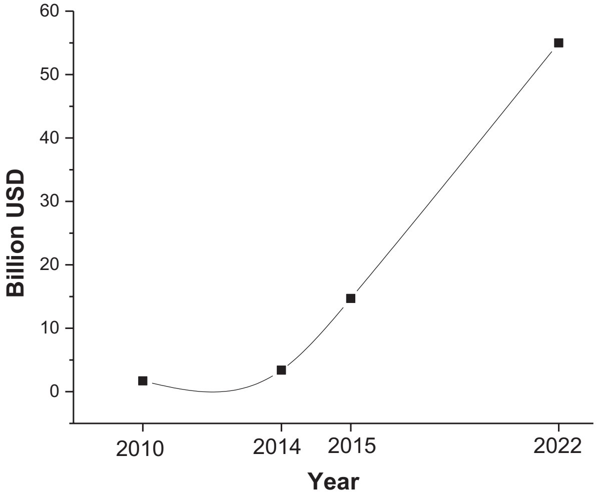

Fig. 1.1 Total worth of nanomaterials in USD (billion) in different years

expected to be the second biggest market for nanomaterials after the USA with over 12% share of the worldwide demand by 2022 (Inshakova and Inshakov 2017). Technology readiness levels (TRL) quantified that carbon-based nanoparticles have a diverse multitude of current uses. In contrast, metal and non-metal oxide-based nanoparticles are the most commonly used in industrial production (Allied Market Research 2016). Around 25% of the nanoparticles introduced in the markets are integrated with TiO_2, SiO_2, and Ag nanoparticles (StatNano 2017). TiO_2 and SiO_2 are the most used up metal and metal-oxide-based nanoparticles, respectively. Ag nanoparticles are considered to be the most commercialized nanoparticles, accounting for over 50% of the global nanomaterial consumer products (Global Market Insights Inc. 2017), with an expected growth market at a CAGR of closely 13% from 2016 to 2024 (Industry Report Forecast 2017). Major areas of Ag nanoparticles consumption are healthcare & life sciences, food & beverages, electronics & IT sectors, and packaging industries (Inshakova and Inshakov 2017). Carbon-based nanomaterials are mostly utilized in coatings, pigments, paints, followed by cosmetics, optics, electronics, clean energy, and the environment (Keller et al. 2013). The industries with top opportunities for applying novel nanoproducts in producing final goods are aerospace, automobiles, electronics, defense, energy storage, and sporting goods industries (Allied Market Research 2016).

Electronics production is estimated to constitute the top stake in the market-approximately 30% in nanoparticle utilization. In contrast, the aerospace industry is the fastest emerging sector in the predicted period because of the growing use of metal oxide nanoparticles, polymer nanocomposites, and anti-corrosion coatings in the aircraft industry (Inshakova and Inshakov 2017). At present, we are procuring the profits of material use reduction, enhanced energy efficiency, and improved performance in numerous prevailing and novel technologies which have been aided by nanoparticle application (Keller et al. 2013). Nanoparticles infiltrate the global economy nevertheless; it is important to understand their environmental repercussions. In 2018, Bundschuh reported that out of 26,00,00,000 to 309,00,00,000 kilograms of global nanoparticle production, about 63–90% ended up in landfills, with the remaining 8–28% discharged into soils, 0.5–7% in water forms, and 0.1–1.5% in the atmosphere. After discharge of nanoparticles in the environment deliberately or accidentally, at different stages throughout the products life cycle, i.e., manufacturing, integration into nano-assisted products and product utilization stage and at the end phase of the life cycle (Gottschalk et al. 2015; Keller and Lazareva 2014) they interact with different constituents of the surroundings and undergo dynamic makeover (Bundschuh et al. 2018). Most nanoparticles like Ag, TiO_2, and ZnO are discharged into the surroundings at the utilization stage. Carbon-based nanoparticles have high adsorption affinities for organic and inorganic pollutants present in the environment. Contact with such pollutants modifies their transference and reactivity (Canesi et al. 2015; Sigmund et al. 2018).

The undesirable casting-off of nanoparticles in surroundings is an impending risk to living beings (Abbas et al. 2019). Coatings, paints & pigments, and cosmetics together combined facilitate 41% of total global nanomaterial flows and likely

Table 1.1 Assessments of nanomaterials released into the environment (air, wastewater treatment plant (WWTP), and soil) during usage in various applications

Application	Air (%)	WWTP (%)	Soil (%)
Aerospace	5	90	5
Automobiles	5	90	5
Coatings, paints & pigments	1	60	35
Cosmetics	1	90	1
Electronics & optics	5	5	90
Energy & Environment	5	5	90
Medical	5	90	5
Packaging	0	5	95
Plastics	1	5	94
Textiles	5	95	0
Sensors	0	5	95

contributed 80–87% of total nanoparticle emissions to soil and 90–97% to water (Keller et al. 2013).

Wastewater treatment plants (WWTPs) serve as an important intermediate passage for some nanoparticles to move from soil and water and vice versa. 17–34% of nanoparticles likely pass through WWTPs, which results in 3–25% release of nanoparticles into water bodies through treated sewage, and 45–47% is discharged to soils through biosolids. The probable nanoparticle releases during use in different applications are presented in Table 1.1, which provides an estimate of the percent release into the atmosphere, water flowing to a WWTP, or release in soil from a waste product. Hence, understanding the behavior and transformation in WWTPs is crucial for the exact estimation of these emissions (Yousaf et al. 2020). United States National Research Council (USNRC) guideline states that "Critical elements of nanomaterial interactions should be considered while estimating the health risks and environmental safety of nanoparticles." (NRC 2012). These critical elements comprise nanoparticles' physical, chemical, and biological changes that oversee their kinesis, bioavailability, persistence, and harmfulness in the environment (Yousaf et al. 2020).

3.1 Guidelines for the Management of Nanoparticles

Rapid commercialization of nanoparticles offers limitless prospects for industrial advancements and economic progress. It holds many keys to old problems, especially in environmental protection, saving energy, agricultural productivity, contaminated soil, and water remediation, reducing hazardous metal wastes and harmful greenhouse gases. However, more expansion and ease of access to nano-based solutions bring several trials which should be brought to notice before further damage is done. Such trials consist of matters associated with monitoring, safe use, and discarding of nanoparticles. Some recommendations made are:

Proper Funding and Manufacturing

First of all, the research done on the influence of nanoparticles on the environment and health is not thought-out as essential and impressive as developing and synthesizing new nanoparticles. This outlook can be understood by observing and comparing the impact factors of research articles and how research funds are distributed. This attitude must change. To make progress and boost research in this area, an adequate amount of funds devoted to toxicity assessment and improvement of safe disposal techniques should be granted by governments, private organizations, or grant funding bodies to study nanomaterials' health and ecological effects (Faunce et al. 2017). Secondly, the company/institute developing the nanoproduct should conduct detailed studies before releasing the product for additional ecological and risk assessment. Proper lab tests should be performed to establish the presence/absence of biotic action or abiotic action is harmful and lethal to the object or not. Tests for product safety must be performed under several ecological settings (i.e., acidity levels, radiation effect, temperature, pressure, moisture, etc.). An authentic, official report clearly describes the chemical structure, industrial procedures, and the required chemicals useful in synthesizing the nanoparticle, analytical processes used to assess lethal and ecological effects of the nanoparticle, along with all up shots collected while performing experiments.

Their port should also mention if the product is safe to manufacture, use, disposal and recyclable (if recyclable, then procedures for recycling). The producer should carefully examine complete information from the readings and submit a concluding report to the controlling body. Experts agree that companies/institutes should be held accountable for assessing risks of their products to ascertain they are safe for manufacturing, using, and disposing off. In cases where such modus operandi do not occur, the corporation/individual using the nanoparticle must be indicted with the duty of completing the toxicity assessment and the developing dumping practices particular to that product (Faunce et al. 2017).

Setting National and International Standards

All countries must develop specific standards based on their different requirements, experiences, and environmental conditions. A nanoparticle could be particularly reactive or toxic under a given set of environmental conditions. National regulatory bodies must handle safe disposal, neutralization of nano-wastes, and systematically collect and preserve information from case studies, concerns, reports, and user grievances associated with the approved product.

Presently, only very few international policies standardize, monitor the safe use and disposal of nanoparticles. International bodies, such as International

Organisation for Standardisation (ISO), have started probing issues at hand and developing criteria linked to safe disposal and/or reprocessing on nano waste. Two important policies regarding nano waste disposal are: ISO/TS 80004, it describes the terminology used in nanotechnology and its uses and presents uniform standards and legislature. One more is ISO/TR 13121:2011. It is more definite as it refers to procedures for detecting, assessing, improving, creating resolutions, and sharing possible threats of developing and using synthetic nanomaterials. Besides, it recommends practices that corporations must follow to be transparent and responsible regarding the management of nanomaterials.

These policies are imperative in handling nanowastes, but they are clearly insufficient. Global support and investments could affect larger and incorporated international policies and schemes, and it will also enrich exchanging novel ideas, concerns, and clarifications. The Organisation for Economic Co-operation and Development (OECD) attempts to address the issue and bring a change in the safe use of nanomaterials by giving out testimonials, reports, and recommendations. Nonetheless, more dynamic science diplomacy is required to standardize the concern, especially at an early stage of product development (Faunce et al. 2017; Campos and Lopez 2019).

Safe Use

Following acceptable work practices help reduce exposure to nanoparticles to a great extent. When working in a lab with nanoparticles, one must always wear personal protective gear, including safety glasses/goggles, lab coats/disposable gowns, respirators/face shields (if the risk of potential aerosol exposure), and nitrile/rubber gloves. Needles used for injecting nanoparticles should not be bent, clipped, or recapped and must be straightaway dumped in sharps containers after use. Bench paper/cloth used during preparing nanoparticle stock should be resistant to limit potential workplace contamination in case of a slight spill. After each work shift, work areas should be cleaned using filtered vacuum cleaners or wet wipes, and pressurized air or dry sweeping should be avoided. Benchtops, safety cabinets, equipments, and lab surfaces should be cleaned regularly, and cleaning must be done in a way that obstructs workers' interaction with wastes. The disposing off nanowastes must conform with central, private, and local guidelines (Amoabediny et al. 2009).

Disposal

The chemical and physical attributes of nanoparticles and their physical properties compel us to recognize ideal removal, neutralization, and recycling procedures for every particle individually. For example, it should not be assumed that disposal measures for Fe_3O_4 nanoparticles shall be applied to TiO_2. Nanowaste removal involves broad investigation; it also needs stringent norms and practices to be adopted. Policymakers, sponsors, scientists, and researchers must come forward and work together for effective and viable principles. Governments should nationally and internationally unite their databases and work with technologists, manufacturers, consumers of nanoparticles to design and improve dependable treaties and strategies for responsible development. Excess stocks and additional waste materials containing contamination in high concentrations must be disposed of through the UTHSC-H Environmental Protection Program. Specific nanoparticles may be unaltered during metabolism hence all potentially contaminated animal remains, bedding, and other materials must be disposed of through incineration. In addition, all contaminated sharp tools and equipments must be placed in a proper sharps container and disposed of as bio-hazardous waste (Amoabediny et al. 2009).

4 Conclusion

Nanoparticles are providing paramount sustainability, health, and welfare expediencies around the globe. Their distinctive physical and chemical properties improve reactivity, strength, electrical features, and functionality. These advantages have ensued in nanoparticles being combined into an extensive series of user products that help protect the environment and climate globally by saving energy, increasing crop yields and agricultural productivity, remediating contaminated soil and water, and reducing hazardous metal wastes and harmful greenhouse gases. But the world has previously known complications that come with novel developments. With the questionable progress of genetically modified foods and the highly relevant microplastics calamity, more progress in applying nanoparticles must result in similar health and safety dilemmas. Health and environmental impacts must be our priority, but this is not an easy job. Even though normal risk evaluations exist for various nano products, every nanoparticle has unique properties, so their safety and disposal measures have to be evaluated following that concerns relating to caution, safe use, removal, and wherever likely, the actual reuse of nanoparticles should be addressed without bias. Widespread applications of nanoparticles have proved beneficial in various fields of sciences, but they are also ascertained hazardous to the surroundings and well-being of mortals. Therefore, it is the need of the hour to have an improved understanding of measures for the safe use and disposal of nanoparticles so that we can more confidently relish their benefits without compromising our environment.

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