Nanotechnology for Environmental Remediation

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Abstract

Nanotechnology has sped up the development and application of innovative technologies that are both cost-effective and cutting edge. These technologies have applications in the remediation of air pollution, catalysis, the detection of pollution, and other areas. The use of nanoparticles in a variety of fields, as well as the impact that they have on the environment, has been confirmed by a number of studies. As a result of their one-of-a-kind qualities and attributes, nonmaterial’s are excellent candidates for the prevention of pollution. This can be accomplished through a reduction in the discharge of industrialized hazardous waste and other contaminants. The exceptional and beneficial properties of nanomaterials include significantly increased surface areas and reactivities, increased electrical conductivity, and increased strength–weight ratios. Nanomaterials can be found in a wide range of applications. Nanotechnology and nanomaterials have contributed to the development of a method that is preeminent in its ability to detect and treat trace environmental contaminants. Within the context of cleaning up air pollution, this chapter explores how a variety of nanomaterials can be put to use. Nanomaterials are being investigated in this research project in the form of nanoadsorbents, nanocatalysts, nanofilters, and nanosensors respectively. It has been suggested that a number of different nanostructures, such as nanoparticles, nanofibers, nanorods, nanosheets, and nanowires, could be utilised in the process of cleaning the air.

Keywords: nanomaterials; environmental contaminants; nanoadsorbents; nanocatalysts; nanofilters; nanosensors

11.1. Introduction

Air pollution is the unintended emission of gases, particulates, and aerosols into the lower atmosphere [1]. This type of pollution is caused by both man-made and natural (such as wind-borne dust, volcanic eruptions, and forest fires) sources. The gases and particles that contribute to air pollution can subsequently pose health risks to humans. Nitrogen oxides, sulphur oxides, hydrogen sulphides, minute dust particles (aerosols), and volatile organic compounds are the most common types of air contaminants (VOCs). According to the World Health Organization (WHO), the combined effects of indoor and outdoor air pollution kill approximately seven million people annually, primarily as a result of an increase in lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, stroke, and acute respiratory infections. WHO data confirms that nine out of ten people breathe in air that exceeds WHO's guidelines for contaminant levels, with the highest exposures occurring in middle-income and low-income countries [2]. Additionally, the WHO is assisting a number of nations in combating air pollution. From urban smog to indoor smoke, air pollution poses a significant threat to climate and health. For the purpose of protecting the environment from the adverse effects of pollution, a number of nations have enacted legislation regulating various types of pollution and mitigating their adverse effects. Nanotechnology is the application of science, engineering, and technology at the nanoscale, which is approximately one to one hundred nanometers. In general, nanotechnology refers to structures with dimensions of 100 nm or less and involves the creation of materials and devices within this size range. Nanotechnology is extremely diverse, ranging from innovative extensions of standard device physics to entirely novel approaches based on molecular self-assembly for the development of nanoscale-sized advanced materials. In nanotechnology, it is also possible to control matter directly at the atomic level. Recent research has focused on nanotechnology's potential to offer advanced solutions to manage and reduce pollution in water, air, and land, as well as to improve the performance of conventional remediation techniques. It is believed that environmental nanotechnology plays a significant role in shaping contemporary environmental engineering and science. Nanotechnology has expedited the creation and application of cost-effective and innovative technologies for air pollution remediation, catalysis, pollution detection, and other applications. Multiple studies [3,4] have confirmed the use of nanoparticles in various fields and their environmental impact. Nanomaterials are ideal candidates for preventing pollution by decreasing the discharge of industrialized hazardous waste and other contaminants due to their unique properties and characteristics. Nanomaterials' exceptional and advantageous properties include significantly greater surface areas and reactivities, greater electrical conductivity, and increased strength–weight ratios. Nanotechnology and nanomaterials contribute a dominant technique for the detection and treatment of trace environmental contaminants. This chapter discusses the use of various nanomaterials in the remediation of air pollution. In this study, nanomaterials in the form of nanoadsorbents, nanocatalysts, nanofilters, and nanosensors are investigated. Various nanostructures, including nanoparticles, nanofibers, nanorods, nanosheets, and nanowires, have been reported for use in air purification. We primarily investigate carbon-based nanomaterials and metal-based nanomaterials for the removal of airborne contaminants. In conclusion, the potential environmental effects of nanomaterials (metal-based nanomaterials and carbon-based nanomaterials) are discussed. Clearly, research studies are devoted to advancing the application of nanomaterials in a variety of environmental remediation applications.

11.1.1. Nanotechnology for Air pollution control and treatment

Photocatalysts become active in breakdown different dangerous air pollutants into less toxic or environmentally favorable products when they are exposed to ultraviolet light. The development of novel photocatalytic materials and their modifications by impregnation might eventually lead to technology for the cost-effective mitigation of environmental concerns. Titania has been significantly changed using metallic and non-metallic dopants to increase its catalytic activity even more. The Novel catalyst, numerous types such as WO_3 decorated ZnO, was also added to the list of photocatalysts to harvest solar light. These many catalysts have been tested to treat various substances and have been used in various situations for pollution remediation[175].Metal-organic frameworks (MOFs) are innovative tools for gas storage and separation, water harvesting from the atmosphere, chemical sensing, energy storage, drug delivery, and food preservation. MOFs have considerable potential for green applications such as air and water pollution remediation due to their diverse structural motifs that may be changed during synthesis. The desire to employ MOFs for environmental applications motivated the addition of metal and functional groups to their structures, as well as the formation of heterostructures by combining MOFs with other nanomaterials to efficiently remove dangerous chemicals from wastewater and the atmosphere [176]

Air pollution, particularly solid particle pollution, poses a major threat to people's physical and mental health. As a result, air filtration membrane performance and stability are becoming increasingly important. Cheng *et al*. d were designed membranes in an in-situ growth method, nanosized polypropylene@zeolitic imidazolate framework-8 (PP@ZIF-8) membranes, and polypropylene@copper(II) benzene-1,3,5-tricarboxylate (PP@Cu-BTC). In a realistic context, these membranes can accomplish effective and stable filtering of PM2.5 particles [177]. Toxic volatile organic compounds (VOCs) and fine particulate matter (PM2.5) in indoor air constitute a hazard to human health, including cancer, leukemia, foetal malformation, and abortion. As a result, developing technology to reduce indoor air pollution is critical to avoid negative consequences. Adsorption and photocatalytic oxidation are the current high-efficiency methods for removing VOCs and PM2.5. Fine particulate matters are particles in the air that are smaller than or equal to 2.5 microns in diameter.PM2.5 are formed inside during fuel combustion, metallurgy, power generation, textile printing, smoke and dust discharged from coal and gas or fuel oil during heating and cooking, and exhaust gas released into the atmosphere when various vehicles utilize fuel in the interior operating operations. Biochar reduces VOCs primarily through two mechanisms: adsorption in the carbonized regime and partitioning in noncarbonized organic matter.[178]

11.1.2.Nanotechnology for water treatment

Rapid urbanization and industrialization have threatened water resource systems, limiting the sustainable development of society and economies. Water pollution, climate change, and high-intensity human activities have a significant impact on watersheds. Around 40% of the population is facing water scarcity. In many countries, the major rivers and lakes are generally subject to different levels of heavy metal contamination. Heavy metal pollution mainly comes from a combination of factors[179] Although natural phenomena such as excessive rainfall can contribute to increased water pollution, manmade activities are the primary causes of heavy metal contamination. The direct flow of dirty water into rivers and lakes, in particular, has expanded dramatically, resulting in heavy metal contamination. Heavy metal contamination exacerbates aquatic pollution and has a direct impact on drinking water safety, food production, and agricultural safety, eventually threatening human health [180]. The present water and wastewater management practice might be considerably improved by introducing nanoparticles into the system, taking advantage of these dimensional effects of Nanomaterials, particularly membranes [181], adsorption [182], catalytic oxidation [183], disinfection, and sensing [184] offer a wider potential and capacity for water and wastewater remediation.

Nanomaterials have increased the competitiveness of water and wastewater cleaning by lowering prices. The use of depleted nanoparticles in water and wastewater treatment systems, on the other hand, remains cumbersome [185]. First, nanoparticles tend to agglomerate in a fluidized system or a stiff substrate, resulting in significant activity loss and pressure decrease [186]. Second, except for magnetic nanoparticles, separating most of the nanoparticles expelled from reused treated water remains a difficult task. It appears to be disadvantageous from a financial standpoint. [187] Thirdly, the actions and implications of nanoparticles in the treatment of water and wastewater are unknown; thus, it is a fundamental worry which can hinder the implementation of nanotechnology [188] that nanoparticles damage human health and the aquatic environment. To avoid or diminish the possible negative effects of using nanotechnology, it is desirable to create a device or material that may reduce the mobilization or release of nanoparticles while retaining their high reactivity. A successful and promising approach has been shown by the development of nano-composites. The most typical technique to create a nanocomposite is to load a range of supporting materials for depositing desired nanoparticles, such as membranes or polymers. It may be defined as a multi-phase material with a diameter of at least one phase of 100 nm [189].

11.1.3. Adsorption & Separation

The two most commonly utilized technologies for polishing water and wastewater are adsorbents and membrane-based separation. The cycle of adsorption regeneration considerably reduces the price-to-benefit ratio of conventional adsorbents. Many Nanosized adsorbents, i.e., metal oxides or Nanosized metal, graphene, nanocomposites, and carbon nanotubes (CNTs), are characterized by excellent selectivity and strong reactivity. They perform adsorption several magnitudes better than conventional adsorbents [190]. Membrane separation is also essential since it allows for the recycling of water from uncommon sources like wastewater. The contamination removal is mostly dependent on size exclusion. However, membrane selectivity/permeability issues still hamper the development of membrane technology, namely trade-offs in membrane selectivity and permeability [191]. Nanocomposite membranes with advanced properties were constructed by including functional nanoparticles into the membrane.

This novel membrane class demonstrated better mechanical or thermal stability, porosity, and hydrophilicity features, including increased permeability, anti-fouling, antibacterial, adsorptive, or photocatalysis [192]. Currently, adsorption and separation nanotechnology are near maturity.

11.2.1.Catalysis

To eliminate trace contaminants and microbiological pathogens from water, the advanced oxidation process of catalytic or photocatalytic oxidation is applied. It's a good approach to making both hazardous and non-biodegradable contaminants biodegradable [193]. Photocatalysis can be used to polish refractory organic molecules [194]. Nanocatalysts with a high ratio of surface to the volume have significantly better catalytic performance than their bulkier equivalents. Size-dependent behavior was also seen in the band gap, and nanoscale semiconductors have a crystalline phase. Their photo-generated charge distribution and electron-hole redox potential changed with different diameters [195]. The immobilizing of nanoparticles onto diverse substances improved the nanocatalyst stability, and the resulting nanocomposites were suitable for contemporary photo-reactors [196].

11.2.3. Filtration and Membrane

Filtration is a physical separation process that allows polluted water to flow through a membrane when larger solutes are present. This method is widely preferred due to its high stability, process intensity, pollutant retention ability, automated process control, lower operational robustness, chemical mass, and filtration [197]. ultrafiltration (UF), a microfilter (MF),Forward Osmosis (FO), Reverse osmosis (RO), nanofiltration (NF), electrodeionization (EDI), electrodialysis (ED), pervaporation, and distillation are currently utilized membrane-based filtration technologies. The macroporous MF membrane traps microorganisms such as bacteria and protozoa as well as suspended particles. (50–1000 µm). The UF membrane with mesoporous holes rejects the majority of viruses and colloidal pollutants (5–50 µm). [198]. The nanoporous NF membrane (0.5–10 µm) is used to remove inorganic and organic pollutants, as well as the ED and EDI procedures are frequently utilized (metals and ions). Water desalination relies on RO and FO membranes with microporous pores (0.1– 1 µm). Desalination can be achieved using distillation or pervaporation, albeit both are less commonly used in practical applications. The downsides of these filtering approaches are low recrudescence, fixed solute selectivity, frequent fouling, and energy-intensive operations. After numerous cycles, most filtering membranes must be cleaned with chemicals and/or heated. (199). As a result, utilizing NMs is required to get the most out of conventional filtration membranes. As proof, we look at the most widely studied (NMs, such as carbon nanotubes (CNTs), ceramic and grapheme, aquaporin, and zeolite membranes, as well as single thin-film composite (TFC) and mixed matrix (MM) membranes. Our goal is to investigate the basics of each NM-based disinfection approach, including the various NMs and production procedures, as well as current commercialization and separation performance attempts. [200].

11.2.4. Nanotechnology for degradation of land waste

Nanotechnology can be applied to contaminated soil, in which pollutants such as heavy metals and metalloids to organic compounds. The technologies included for the removal of impurity are immobilization, reduction reaction, photocatalytic degradation, Fenton and Fenton-like oxidation, and various combinations of the abovementioned mechanisms. The combination of nanotechnology and bioremediation (e.g., phytoremediation and micro-remediation) has also become popular in recent years [201, 202]. The organic pollutants are often detached by catalytic degradation and reduction reaction, whereas pollutants like heavy metals and metalloids are removed by an adsorption mechanism. Some researchers adopted methods and materials that can simultaneously remove multiple pollutants [203]. In a simultaneous adsorption and oxidation scenario, the presence of ENMs could facilitate both adsorption and redox degradation of micropollutants [204]. The demand for these multifunctional Nanomaterials is increasing due to the efficient removing capacity, time consumption, avoid sequential processing of pollutants. The researchers have worked out on

Fig.11.1. Soil Pollution Remediation Classification

Heavy metals and organic compounds such as carbon nanomaterials, metal oxides Fe_3O_4, TiO2, ZnO, nanoscale zero-valent iron (nZVI) nanoparticles, and nanocomposites. Figure 1. shows classification according to their pollutant removal mechanisms.

Nanotechnology has proved extensive attention in the removal of soil contaminants. The Nanoscale metal oxide such as iron-free, Fe_2O_3, cerium oxide, Al_2O_3, Mn_xO_y, TiO_2,and MgO shows the good result for soil remediation [205]. Recently magnetic nanosized adsorbents have been used for removing magnetic impurities from soil [206]. Several researchers found that nanomaterials are extremely adsorbent properties towards heavy and toxic metals arsenic, cadmium, chromium, and uranium. Besides these, they outdo the high capacity and selectivity of other common contaminants, such as organic and phosphate. Emulsified nanoscale zero-valent iron (ZVI) nanoparticles are environmentally safe treatment particles that eliminate contaminants from water. Compared to conventional treatment methods, EZVI requires less treatment time and produces less waste. EZVI is a viable solution for polluted areas that have a high contaminant load. Currently, EZVI is used at several sites, including dye manufacturing facilities, pharmaceutical and chemical manufacturing facilities, dry cleaners, and metal cleaning and degreasing facilities. Several government-owned sites have also begun using EZVI to remove contaminants from groundwater. [206, 207, 208]. The effectiveness of EZVI depends on several factors, including the soil pH and the concentration of the contaminant. The nanoscale particles are attracted to each other, promoting efficient transport. In addition, nZVI nanoparticles can agglomerate into larger micron-sized particles. However, the lack of toxicological information poses a major challenge. It is crucial to identify methods of controlling migration that minimize the risk of toxicological effects. The use of nZVI in environmental clean-up is a promising approach for removing pollutants from groundwater. Moreover, it is inexpensive. EZVI is the only commercially available agent with these features. For example, nanohydroxyapatite particles are effective in controlling soil surface crust formation. This technology is the future of environmental clean-up. Although the potential benefits of using engineered nanomaterials in environmental clean-up are enormous, concerns about their safety and sustainability still surround their widespread use. While engineered nanomaterial (ENMs) can improve food production and produce more energy and clean water, they have raised significant environmental concerns. Many studies have found adverse effects in the soil, air, and water. Furthermore, their use has led to a plethora of misleading information and misunderstanding. The benefits of engineered nanomaterials for environmental clean-up include the potential to remove contaminants from the surface and groundwater. EnMs can be designed to perform chemical reduction, sorption, and complexation. When synthesized at the nanoscale, ENMs exhibit altered properties, which make them highly effective in decontamination [209]. These nanomaterials are also highly efficient at decontamination because they have large surface areas and catalytic activity. Nanomaterials can be used to remove pollution from soil and water and are also effective for removing pesticides, dyes, and heavy metals.

Plastics' exponential use and refractory characteristics result in their massive environmental build-up, a severe environmental concern that modern cultures are presently confronted with. The presence of plastic garbage in many environmental matrices can have major consequences for living forms, ecosystems, and the economy. Furthermore, plastic trash can degrade into smaller particles known as microplastics (MPs) and neoplastic (NPs), resulting in new interactions with the environment and living beings. As a result, there is an urgent need to create long-term and cost-effective mitigating options. Because plastic-degrading enzymes may selectively target the polymer structure for subsequent breakdown, enzymatic techniques stand out as viable, sustainable strategies for microplastic degradation. Because plastic-degrading enzymes may selectively target the polymer structure for subsequent breakdown, enzymatic techniques stand out as viable, sustainable strategies for microplastic degradation [210,211,212].

Extracellular hydrolase enzymes that break down long-chain polymers into smaller molecules include lipases, proteases, and cellulases. These enzymes, in general, promote hydrolytic cleavage of lengthy chains, resulting in smaller units that are simpler to transport and absorb into the cell for further enzymatic destruction and, eventually, the release of ecologically innocuous chemicals [213]. Different enzymes have also been immobilized on inorganic nanostructures. For instance [214] Covalent bonding immobilized lipase and cutinase on SiO_2 nanoparticles and Fe_3O_4@SiO_2 nanostructures. The constructed catalytic systems degraded polycaprolactone with remarkable stability and efficiency. Carbon-based materials, on the other hand, have shown promise as a support for plastic-degrading enzymes. Cadmium (Cd) contamination in paddy soil has harmed human health significantly. Because of their outstanding adsorption efficiency and mechanical robustness, nano-ferrous sulfide@lignin hydrogel

(FeS@LH) composites might be an appropriate material for paddy soil Cd removal. However, the FeS@LH's performance in a paddy field is unknown. In this investigation, FeS@LH was used to establish water spinach in a Cd-contaminated paddy area (Ipomoea aquatica Forssk). After 30 days, FeS@LH efficiently eliminated Cd from the soil (37.6%) and water spinach (34.5%). Pb, Zn, Cu, and other metal concentrations in soil and water spinach were determined [215].

11.2.5.Nano-Particles as adsorbent

Advanced nanoadsorbents demonstrate a significantly increased adsorption rate for removing gases, bacteria, and other organic compounds from the environment, in comparison to conventional adsorbents' low efficiency and limited active site surface area. The characteristics of adsorption are highly dependent on the nature of the adsorbent; particularly its surface areas and porosity. Due to their greater affinity for CO_2, carbon-based materials such as CNTs, activated carbon, and carbon fiber composites have been developed as potential adsorbents [5]. Recent interest in the use of CNTs for the adsorption of CO_2 has increased due to their reversible nature, in which the CO_2 adsorption can be reversed through desorption as the temperature rises.

Amine-functionalized CNTs are regarded as promising CO_2 capture adsorbents. Amine groups can react with carbon dioxide to form bicarbonate and carbamate ions [5] CNT is a suitable support for adsorbents due to its greater surface area and chemical stability, which reduces the likelihood of adsorbent denaturation during the CO_2 adsorption process. In a study by [6], superior adsorbents for CO_2 capture were prepared by amine functionalizing multi-walled CNTs with (3-aminopropyl)triethoxysilane in a two-step process; that is, acid pretreatment with sulfuric acid and nitric acid, followed by amine functionalization with (3-aminopropyl)triethoxysilane. The amine-functionalized multi-walled CNTs performed better in the CO_2 adsorption test, contributing to the greatest CO_2 uptake of 75.40 mg CO_2 adsorbed/g adsorbent. Due to their exceptional chemical and physical properties, ZnO nanostructures have attracted a great deal of research interest, resulting in numerous opportunities for energy, environmental, and electrical applications. Due to their thermal stability for the non-catalytic suffixation reaction [7], the use of zinc oxide nanostructures for hydrogen sulphide removal from the air, particularly at higher temperatures via an adsorption mechanism, is intensively studied [8] described a simple single-step technique involving ultrasonic-assisted precipitation with no surfactants and post-heat treatments for preparing ZnO nanoparticles and their application for adsorbing H_2S from the air. The results of adsorption tests confirmed that the prepared zinc oxide Nano adsorbent had a greater capacity for hydrogen sulphide adsorption due to the very high air volume treated and longer adsorption time. The aforementioned study confirmed that the prepared zinc oxide Nano adsorbent is an extremely promising material for various ecological applications. SO_2 is an odorless, nonexplosive, and noncombustible gas that can impart a taste to the air at concentrations between 0.30 and 1.0 ppm. In the atmosphere, SO_2 will transform into extremely stable byproducts. SO_2 is emitted into the atmosphere by the combustion of sulfur-containing fossil fuels and other industrial processes [9,10] reported results from single gas adsorption, confirming that zeolites are highly effective at removing CO_2, SO_2, and nitric oxide[11]. confirmed that iron nanoparticles with a size of approximately 3–4 nm increased the SO_2 adsorption capacity by nearly 80% by providing dispersed reactive centers. Sekhavatjou *et al*. [12] investigated the separation of sulphur components from sour gas using nanoparticles of zinc oxide and iron oxide. Mahmoodi Meimand *et al* [13] investigated the application of two nanomaterials, clinoptilolite zeolite with iron oxide nanoparticles and natural clinoptilolite zeolite, as nano adsorbents for the SO_2 adsorption. Due to the regenerative nature of the iron oxide nanoparticles, the modified zeolite with iron oxide nanoparticles exhibited greater SO_2 absorption efficiency than the unmodified zeolite. This could be considered an effective, trustworthy, and practical method for removing SO_2 from the air. Several studies [14] on the use of MOFs as nanoadsorbents for removing nitrogen and sulphur compounds from gas streams have been published. Among these MOF-based nanoadsorbents, NH2-substituted UiO-66 exhibited a greater acid gas (e.g.,CO_2, H_2S, NO_2, and SO_2) adsorption capacity. UiO-66-NH2 has the capability of adsorbing noxious gases in a matter of minutes, making it a potential material for detoxification. Variable pore size, increased porosity, and higher concentrations of UiO-66-NH2 make it an ideal material for the removal of acid gases [15].

Table 11.1: Carbon-based nanoadsorbents for the removal of different environmental contaminants

Nanoadsorbent	Contaminants	Sorption capacity	pH	Time	Kinetics	Isotherm models	References

MWCNT-TYR	Methylene blue	440 mg/g	6	7	Pseudo-second order kinetic	Langmuir isotherm model	[211]
MWCNTs(5–15nm)	Pb(II) Ni(II)	215.38±0.03 mg/g 230.78±0.01 mg/g	5	60	Pseudo-second order kinetics	Langmuir isotherm model	[66]
MWCNTs[16–25nm)	Pb(II) Ni(II)	201.35±0.02 mg/g 206.40±0.02 mg/g					
AminMag MWCNTs@SiO2	Pb(II) Cd(II)	98–104%	8	5	Pseudo-second order kinetics	Langmuir isotherm model	[19]
Single-walled carbon nanotubes magnetic nanoparticles (SWCNT-MN) hybrid adsorbent	Xyline	50 mg/g	8	20		Langmuir–Freundlich(GLF) isotherm	[42]
Nitrogen-doped graphene oxide nanosheets (N-GO)	Congo red	98–99%	2	360	Pseudo-second order kinetics	Langmuir isotherm model	[36]
Graphene oxide	Basic red 46	370.4mg/l	11	30	Pseudo-second order kinetics	Langmuir isotherm model	[67]
Magnetic graphene oxide impregnated with polystyrene (GO-PSm)	Bisphenol A	50.25 mg/g	3	60	Pseudo-second order kinetics	Langmuir isotherm model	

MGO impregnated with chitosan (GO-CSm)		86.22 mg/g					
MGO impregnated with polyaniline (GO-PANIm)		31.76 mg/g					

11.3.1. Nano-Particles as catalysts

Nano-based photocatalysis is a potential method for purifying atmospheric air contaminants, and it has received increased research focus in recent years. Photocatalysis can be utilized for a variety of environmental applications, such as water disinfection, air purification, and unsafe water remediation, due to its enhanced capability of converting photon energy into chemical energy for rapidly degrading and mineralizing persistent environmental pollutants [16]. The separation efficiency of air contaminants depends heavily on the phase structure, surface texture, and morphology of nano-based photocatalysts. Recent emphasis has been placed on the development of nano-based photocatalysts with a porous structure and explicit chemisorption toward target contaminants. This is because it allows low-concentration reactants to freely accumulate on the surface of nano-based photocatalysts, which could improve photocatalytic performance [17]. Photocatalysis with modified TiO_2 has the potential to enhance both air quality and health. Smart coatings, which are standard materials suitable for interior applications, are produced by modified TiO_2 with advanced photocatalytic properties under interior light irradiation. It is generally accepted that photocatalytic performance is affected by light absorption, surface reactivity, and charge creation/recombination rate. The use of photocatalytic materials and coatings based on TiO_2 as an exterior layer on building facades along high-traffic roads has proven effective at degrading significant air pollutants, such as nitrogen dioxide, produced by vehicle exhausts. The effectiveness of TiO_2-containing paints in separating nitric oxide under controlled environmental conditions of illumination, temperature, and humidity is evaluated. In addition to the mineralization of inorganic and organic substrates, photocatalysts based on titania have the potential to eradicate a vast array of microbes [18].

Binas *et al*. [19] demonstrated that the separation of NOx gases and VOCs at standard outdoor or indoor air levels using a photocatalytic technique based on titania is feasible. In addition, titania-based photocatalysts have garnered considerable interest in recent years as disinfectants for a variety of microbes, including those that are highly persistent in the environment, such as protozoan cysts, bacterial spores, and viruses. Both VOC and NOx photodegradation are affected by humidity. Due to the competition between water molecules and contaminant molecules for adsorption sites, an increase in relative humidity stops photooxidation. Rezaee *et al*. [20] investigated the photocatalytic decomposition of gaseous formaldehyde over nanoparticles of zinc oxide on bone char. According to test results, the maximum decomposition efficiency of formaldehyde was approximately 73%. The results also confirmed that the immobilization of ZnO nanoparticles on bone char has a synergistic effect on photocatalytic degradation. This is a result of the stronger adsorption of formaldehyde molecules on bone char, which results in increased diffusion to the catalytic zinc oxide and a consequently high photocatalytic rate. Vohra *et al*. [21] created a silver-ion-doped titania-based photocatalyst with enhanced microorganism destruction in the air. The performance of a silver-ion-doped photocatalyst is confirmed using a catalyst-coated filter in an air-recirculating experimental setup. MS2 Bacteriophage, *Aspergillus niger, E. coli, Staphylococcus aureus, and Bacillus cereus* were used as indices to demonstrate the improved photocatalytic process's enhanced disinfecting capacity. The ability of this enhanced photocatalyst to degrade microorganisms was found to be one order of magnitude greater than that of a typical titania-based photocatalyst. This enhanced photocatalysis process is effective against higher concentrations of airborne microorganisms, making it a viable alternative for bioterrorism defense.

11.3.2.Nanotechnology for Removal of Organic Contaminants

There are alcohols, carboxylic acids, phenolic derivatives, and chlorinated aromatic compounds among the organic contaminants in the environment. Photocatalytic degradation is one of the most acceptable methods for degrading hazardous organic contaminants. The organic contaminants can be converted to carbon dioxide and water via photocatalytic degradation. Organic dyes produced by industries are an additional significant organic contaminant. By means of photocatalysis, certain metal ions are capable of degrading these dyes. Figure 2. illustrates the photocatalytic degradation of metal and organic contaminants.

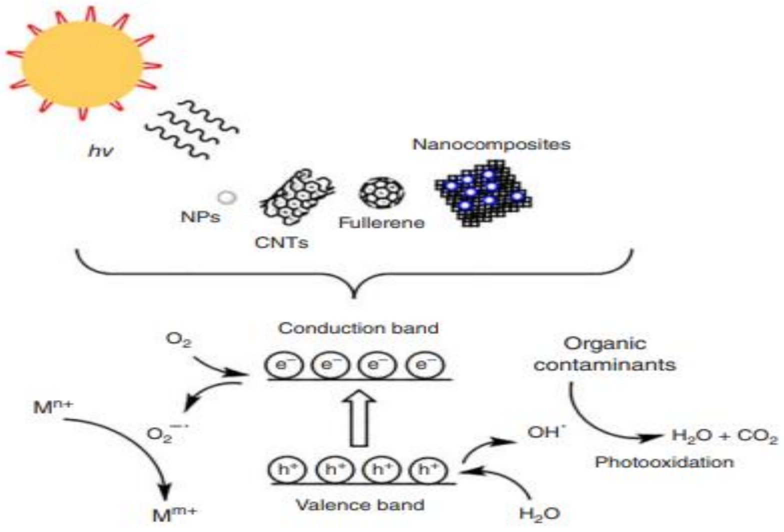

Fig.11. 2. Photocatalytic degradation mechanisms of metal and organic contaminants. Source: Guerra *et al*.[22] /MDPI/Licensed under CC BY 4.0.

11.2.4. Nanosensors

Diverse nanomaterials are presently used to create fast-responding nanosensors with piezoelectric, thermal, optical, and electrochemical properties for detecting chemical compounds present in extremely low concentrations (as low as 1 ppb) [22]. Graphene, carbon nanotubes, metal, and metal-oxide-based nanoparticles are examples of nanomaterials used in sensor applications. These nanoparticles are tailored for sensing and measuring various air contaminants, such as toxic gases (e.g.,NO_2, H_2S, and SO_2) and heavy metal ions. In the sections that follow, various nanotechnology applications for the detection of toxic gases such as NO_2, H_2S, and SO_2 are discussed.

3. Detection of Toxic gases and Greenhouse gases:

11.3.1. Detection of nitrogen dioxide (NO_2)

Nitrogen dioxide is a prevalent air pollutant that is primarily observed as a mixture of nitrogen oxides (NOx) in varying proportions (x). This gas is toxic, irritant, and reddish-brown in color, with a distinct pungent and stinging odor. Graphene-based materials are ideal candidates for the development of room-temperature gas sensors due to their superior properties, such as good chemical and physical stability, increased surface area, and improved carrier mobility at room temperature [23, 24]. A potential method for obtaining high-performance r-GO-based sensing materials is to modify the surface of r-GO using covalent or non-covalent techniques to alter its semiconductor properties. Using r-GO-multiwalled CNTs–tin oxide nanoparticles hybrids as sensing materials, which were produced by hydrothermal treatment of graphene oxide (GO)-multiwalled CNT dispersion in the presence of tin tetrachloride [25], an improved NO_2 nanosensor has been developed. Initially, the sensor based on r-GO-multiwalled CNTs–tin oxide nanoparticles hybrids demonstrated a good recovery rate, fast response, improved selectivity, and enhanced stability for detecting nitrogen dioxide at room temperature, which is considered to be superior to previously reported r-GO-based NO_2 sensors.

Agarwal *et al*. [26] reported a reliable and flexible chemoreceptor-type nitrogen dioxide gas sensor based on CNTs with a single wall on PTFE membrane filter substrates. This sensor is created by using a cost-effective spray coating to prepare a thin film of single-walled carbon nanotubes, followed by the preparation of metal contacts using a shadow mask and polyethyleneimine noncovalent functionalization of the single-walled carbon nanotubes. This exhibited greater sensitivity to nitrogen dioxide gas at room temperature in dry air, 167.7–21.58% for concentrations of 5–0.75 mg/l, compared to ammonia, which was almost insensitive. Wang *et al*. [27] developed a molybdenum disulfide nanoparticle–incorporated r-GO hybrid material for the detection of nitrogen dioxide using a two-stage wet-chemical method. Compared to conventional metal oxide–based semiconductor gas sensors, CNT–based gas sensors offer several advantages, including higher sensitivity, lower operating temperature, and lower power consumption [28, 29] developed selective and ultrasensitive gas sensors based on solution-processed single-wall CNT random networks for room-temperature detection of nitric oxide down to parts per billion. These sensors demonstrated a 50% response in both air and inert atmospheres, with a detection limit of 0.20 ppb and a selectivity toward various contaminant gases of volatile organic compounds, including ammonia, toluene, and benzene. The photo desorption energy attained by ultraviolet irradiation reduced the recovery time of these cutting-edge nitric oxide gas sensors to a few tens of seconds. Furthermore, silicon ox carbonitride functionalization is suggested for improved reliability, reproducibility, and stability in CNT-based gas sensors [30]. Following heat treatment, a thinner layer of the semiconducting ceramic silicon ox carbonitride is developed on the CNTs. This method is extremely straightforward, as the liquid precursor completely coats the CNT surfaces without requiring surface modifications. This advanced conductometric gas sensor can detect up to 10 ppm of ammonia and 2 ppm of nitrogen dioxide at temperatures as high as 350^0 C.

11.3.2. Detection of Hydrogen Sulfide (H_2S)

H_2S is an irritant and toxic gas at concentrations as low as 100 parts per million. Extremely selective and sensitive gas sensors can help protect humans and the environment from flammable and odorless gases. For the detection of H_2S, various metal oxide–based sensors are utilized, with zinc oxide regarded as the superior gas-sensing material. This is due to its exceptional properties, such as chemical stability, non-toxicity, and ease of synthesis in various nanostructure classes, including nanosheets, nanorods, nanocrystalline structures, and nanowires [31,32] synthesized colloidal ZnO quantum dots using a simple colloidal technique with oleic acid as a surface-capping ligand. Due to their superior solution processability, simplicity of integration, and low cost, CQDs are becoming viable candidates for gas sensors. On ceramic substrates, properly dispersed zinc oxide CQDs were spin-coated for the development of chemi-resistive gas sensors. The film-level ligand-exchange treatment was utilized to remove the long-chain surface-capping, thereby facilitating both gas adsorption and carrier transport. With a response of 113.5 upon exposure to 50 mg/l of hydrogen sulphide at room temperature and a response time of 16 seconds, the ideal sensor demonstrated superior performance. Results demonstrated that zinc oxide CQDs are viable candidates for high-performance gas sensors. Nanocomposites of metal oxide and graphene are becoming promising candidates for the fabrication of high-performance gas sensors. Song *et al.*, [33]. Demonstrated sensitive H_2S gas sensors based on tin(IV) oxide quantum wires anchored to r-GO nanosheets at room temperature. Due to the r-GO steric hindrance effect, the morphology-related quantum confinement of tin(IV) oxide could be properly controlled using a single-step colloidal preparation method by adjusting the reaction time. For the development of chemi-resistive gas sensors, tin(IV) oxide quantum wire/r-GO nanocomposites were spin-coated on ceramic substrates without additional sintering. The optimal sensor response to 50 ppm H_2S is 33 in two seconds and is completely reversible upon H_2S release at 22 degrees Celsius. These sensors are extremely advantageous for the ultrasensitive detection of H_2S gas with reduced power consumption due to their easy fabrication and operation at room temperature. Shanmugasundaram *et al.* [34] created hierarchical mesoporous nickel oxide nanodisks and boron–nitrogen co-doped r-GO nanodisk composites for H_2S detection. The response of the boron–nitrogen co-doped r-GO nanodisk composite sensor to 100 mg/l H_2S at 150 C was nearly 82, and the sensor demonstrated a detection limit of about 24 ppb. In addition, the sensor's responses were twofold and threefold stronger than those of pristine r-GO incorporated nickel oxide and nickel oxide nanodisk sensors, respectively. This boron–nitrogen co-doped r-GO nanodisk composite sensor is ideal for potential practical applications, particularly in explosive environments and in medical diagnosis, due to its simple preparation method, superior sensitivity, high stability, rapid response, selectivity, and operation at ambient temperature.

11.3.3. Detection of sulphur dioxide (SO_2)

SO_2 is considered to be the primary pollutant in vehicle exhaust, thermal power plant emissions, and chemical production processes [35]. In addition, SO_2 gas is an atmospheric environmental contaminant and a hazardous gas with a human tolerance of approximately 5 ppm, which can lead to severe diseases such as lung cancer, cardiovascular disease, and respiratory disease. Using a first-principles method based on spin-polarized density functional theory, Shao *et al*. [36] demonstrated that intrinsic graphene should not be considered an effective material for SO_2 absorption. Ren *et al*.[37] fabricated anSO_2 gas sensor with chemical vapor deposition-grown graphene configured in a field effect transistor device and demonstrated its detection properties at a concentration of 50 ppm SO_2. Zhang *et al*. [38] demonstrated the ultralow SO_2 gas sensing capabilities of a self-assembled TiO_2/graphene film device at room temperature. The developed film was produced by the alternate deposition of TiO_2 nanospheres and GO to form a nanostructure, followed by the reduction of GO into r-GO. At room temperature, the gas-sensing properties of assembled TiO_2/r-GO hybrid were analyzed against lower concentrations of SO_2 gas. This SO_2 gas sensor demonstrated ppb-level detection, good reversibility, rapid response and recovery, selectivity, and repeatability. This sensor's potential sensing mechanism was due to the synergistic effect of TiO_2 and r-GO, as well as the unique interaction at titanium dioxide/r-GO interfaces. This study demonstrated that the prepared TiO_2/r-GO film sensor has potential applications for the detection of SO_2 due to its superior sensing capabilities, lower power consumption, and low cost. Liu *et al*. [39,40,41] fabricated zinc oxide nanosheets adorned with ruthenium/alumina catalyst and incorporated this material into a microsensor for the detection of SO_2 gas. Petryshak *et al*.[42] demonstrate the spectral characteristics of cholesteric–nematic mixture intercalated with single-walled CNTs, double-walled CNTs, and multi-walled CNTs under the SO_2 effect. The study confirmed that the composite's sensitivity varies depending on its composition and demonstrated that the highest spectral sensitivity coefficient is observed at nanotube concentrations of 0.30 percent.

11.3.4. Heavy Metal Detection and Removal

Nanoparticles are predominantly used as adsorbents to remove heavy metals. NMTs, including zero-valent iron, magnetite, graphene, and carbon nanotubes, have unique properties, including a high surface-to-volume ratio, stability, inertness, reactivity, and biocompatibility, that makes them a promising candidate for adsorption. Heavy metals, like organic compounds, are nonbiodegradable and accumulate in food chains, affecting humans and animals [43,44]. In recent years, nanomaterials based on iron have emerged as a leader in removing heavy metal contamination from aqueous solutions. Zero-valent iron is widely used for the adsorption of Pb_2+ (Lead), Ni_2+ (Nickel), Zn_2+ (Zinc), Cd_2+ (Cadmium), Cr+6 (Chromium), and Cu_2+ (Copper) as a result of its robustness, ease of synthesis, and reduction property. Azzam *et al*. [45] extracted Pb(II), Ni(II), Cu(II), and Cd(II) ions from an aqueous solution using nano-zero valent iron (nZVI). The following order of maximum adsorption capacity (qmax) was observed: Pb_2+ (1666 mg/g)>Cu_2+ (181 mg/g)>Cd_2+(151 mg/g)>Ni_2+(133 mg/g). The authors illustrated that the metal ions were initially physically adsorbed on the surface of nZVI and then co-precipitated. The pH of the solution primarily affects the removal rate of metal ions, which suggests that the formation of FeOOH on the surface of nZVI enhanced the adsorption rate. Reduction is an additional mechanism observed during heavy metal remediation. In their review, Fu *et al*.[46] described the reactions involved in chromium reduction. The hexavalent state of chromium (Cr+6) was identified as a toxic environmental contaminant; therefore, it must be converted to a nontoxic form (Cr+3). Through electron transfer, the iron particles are oxidized to Fe+3 ions, and the hexavalent chromium is reduced to Cr+3 (Equations (4.1) and (4.2)). Iron and chromium are subsequently precipitated as Fe and Cr hydroxides. However, nZVI suffers from aggregation due to its magnetic nature, reducing the nanoparticles' reactivity. This problem is resolved by immobilizing nanomaterials on a substrate, which may be composed of polymer, metal, or porous material.

$$Cr_2O_2 - 7 + 2Fe + 14H++ \rightarrow 2Cr_3+ + 2Fe_3+ + 7H_2O \quad (4.1)$$

Cr_3+ plus Fe_3+ plus 6OH yields $Cr(OH)_3$ and $Fe(OH)_3$ (4.2)

In addition to nZVI, other magnetic nanomaterials, such as Fe_3O_4, are utilized to remove heavy metals. Shi *et al*. [47] synthesized Fe_3O_4 nanoparticles via a green synthesis process employing flavonoid polymer complex proanthocyanidins (PAC) and used them for the adsorption of Pb_2+, Cu_2+, and Cd_2+ from water. The highest removal rates for Cu_2+, Cd_2+, and Pb_2+ were 96%, 91%, and 87%, respectively. According to their research, the presence of hydroxyl ions in PAC coordinates with metal ions and forms a surface complex with Fe-PAC, which increases the adsorption rate. Lin *et al*. [48] utilized magnetic iron oxide nanoparticles (Fe_3O_4 and -Fe_2O_3) in a coexisting system to treat As(V), As(III), and Cr(VI). The removal mechanism is attributable to the formation of an outer sphere composed of hydroxyl ions and an inner sphere-forming complex composed of metal ions. Due to the stronger binding energy of As(V) (0.39 eV) than As^{3+} (0.35 eV) and Cr^{+6} (0.26 eV), As(V) ions displace As(III) and Cr(VI) from the outer sphere of iron oxide nanoparticles, resulting in a high affinity of iron oxide nanoparticles for As(V) ions. For the removal of additional metal ions (Cr(VI) and As(III)), a greater quantity of nanoparticles was required at higher pH values. For the treatment of metal ions, nanofiber membrane filtration was also employed. Liu *et al*. [49] utilized nanofibrous composite membranes modified with polyacrylonitrile (PAN) and polyvinyl alcohol to remove chromium and cadmium from contaminated water (PVA). The amino groups present on the surface of the PAN-modified membrane result in a higher Cr^{+6} (66 mg/g) and Cd^{+2} (33 mg/g) adsorption rate. In addition, nanomaterials can serve as catalysts in a variety of degradation processes.

Non biodegradable heavy metals such as arsenic, chromium, cadmium, lead, mercury, zinc, and nickel are considered environmental pollutants. Consequently, they accumulate in nature and can enter the living system, causing severe toxic effects such as kidney damage, abdominal pain, hypertension, dyspepsia, nausea, headache, and nasal and lung cancer. For the removal of metal ions and metals, several mechanisms are available, including physical adsorption [50,51}, ion exchange, electrostatic interaction and hard/soft acid-base interaction [52]. Carbon-based, polymeric, magnetic, or nonmagnetic nanoadsorbents [53], biopolymer-based, metal oxide-based [54], and zeolites are examples of nanoadsorbents that can be used as heavy metal adsorbents. Due to their large specific surface area, ease of chemical or physical modification, and high adsorption capacity, carbon-based nanomaterials are effective for the removal of heavy metal ions. CNTs have numerous active adsorption sites on their surface, interstitial channels, internal sites, and external groove sites [55]. The adsorption capacity of carbon nanotubes [CNTs) can be enhanced through physical or chemical modification [56]. Hayati *et al*. [57] utilized CNT modified with four generations of poly-amidoamine dendrimer [PAMAM, G4) to remove Cu^{2+} and Pb^{2+} from an aqueous solution. They concluded that PAMAM/CNT nanocomposites are super-absorbent, capable of absorbing large quantities of heavy metal from liquid phases with a single or binary component. Researchers prepared a composite of CNT by combining fullerene CNT with zinc ferrite ($ZnFe_2O_4$) in order to improve the adsorption capacity of fullerene CNT. They discovered that crushing fullerene CNTs with $ZnFe_2O_4$ composite improved the adsorption performance of free fullerene CNTs by 25% for Hg(II), Pb(II), Cd(II), Elsehly *et al*. [58] fabricated CNT-based filters by modifying CNT with ion-beam irradiation; the filters exhibited an increase in Mn(II) removal efficiency of up to 97.5% as a result of the high disorder in the irradiated samples. It was discovered that biopolymer-based heavy metal removal is efficient, environmentally friendly, and cost-effective. Charpentier *et al*. [59] utilized magnetic carboxymethyl chitosan nanoparticles for heavy metal ion adsorption. They discovered that the magnetic properties of the nanoparticles enhanced the heavy metal ion adsorption capacity.

11.3.5.Nanomaterials towards Clean Energy storage and generation

Nanotechnologies offer potential benefits in every aspect of the energy industry, from production to transmission, distribution, conversion, and consumption, because they enable alternative solutions for energy generation, storage, and conservation. Nanotechnologies and nanomaterials have experienced significant global diffusion in recent years, as measured by the number of active companies, the number of consumer goods available on the global market, and the number of workers employed in all their sectors. Nanotechnologies are among the six key enabling technologies (KETs) considered by the Horizon 2020 program of the European Commission. In tandem with the enormous potential demonstrated by nanoscale materials, scientists have focused on examining their potential effects on human health at each stage of their life cycle. The parameters that can affect the toxicity of nanomaterials are affected by environmental conditions and can change over time. Diverse international initiatives are geared toward risk assessment and exposure monitoring. In the absence of toxicological information, control banding (CB) strategies are used to prevent exposure to specific agents that are potentially hazardous, providing a risk assessment. In recent decades, the principles of CB have been applied to the management of chemical risk in a variety of contexts, including industrialized nations, emerging economies, and developing nations. The danger bands are identified by assigning a risk score to nanomaterials based on their emission and exposure potentials. Emerging and innovative technologies have the potential to penetrate the market and profoundly alter its dynamics, with changes that have a significant economic, environmental, and social impact on the local production system and the global system.

The associated green growth strategies can contribute to fiscal consolidation and the creation of new employment opportunities [60] thanks to the objective of increasing productivity through greater efficiency in the use of energy and natural resources. They can also provide opportunities for economic growth and improved well-being.

There are numerous widely used tools for assessing sustainability and eco-innovation; they are based on "life-cycle thinking," evaluations of value chains (value chain case studies), and potential risks, such as risk assessment. Social issues surrounding nanotechnology must not only be comprehended and evaluated downstream but also in decision-making and upstream research in order to ensure that technological development meets global social objectives. Nanotechnologies can lead to a revolution that reshapes economies, the job market, trade, international relations, social structures, civil liberties, our relationship with the natural world, and even our conception of what it means to be human, with rapid transformations in health care, energy supply, communications, and defense. Concerning the potential negative effects of nanotechnologies, the problems arising from already existing socio-economic injustices and the unequal distribution of power may worsen, creating greater inequalities between rich and poor people by widening the gap between those who control these new nanotechnologies and those who are excluded from using their products and services. Nanotechnology may destabilize international relations as a result of a race for nano-weapons, an increase in the potential for biological weapons, and the use of surveillance tools with significant negative effects on civil liberties. Transhumanists view nanotechnology as a mechanism for altering human nature itself, going beyond curing diseases and enhancing human characteristics, but even this perspective can have negative effects on global societies. The present contentious and delicate global situation regarding the use of vaccines is instructive. Over the past few decades, the frequency of scientific reports on engineered nanomaterials (ENMs) and, consequently, their potential for application has increased. These materials have a place in every sector of production, including agro-zootechnical and food production.

Due to its numerous applications in daily life and impact on scientific fields, such as the pharmaceutical industry, the energy industry, the food industry, medicine, space exploration, and electronics, enzyme nanotechnology has garnered considerable attention in recent years [61]. Various properties of nanoparticles can alter the structure and function of enzymes when they interact with nanoparticles. Enzyme nanoparticles have numerous applications in various industries and have widened the scope of research for scientists and explorers to develop novel goods. The following are the various advantages of using nanoparticles for enzyme immobilization:

a) Large surface area

b) Mass transfer resistance

c) Efficient enzyme loading

d) Enhanced mechanical strength

e) Minimization of diffusion issues

The production of enzyme nanoparticles is a method for designing biosensors [62], biofuel [63], biodiesel [64], and enzyme. Due to their low cost, eco-friendly qualities, and important roles in the diagnosis and treatment of diseases, they are also used to manufacture biomedical devices [65]. By immobilizing enzyme matrices on nanoparticles, enzyme stabilization is more effective and simpler than conventional methods [66]. Enzymes immobilized on nanoparticles are also effective in enzyme prodrug therapy and the treatment of cancer [67].

4. Toxicity of Nanomaterials

While almost anything can be toxic in sufficient quantities, the pertinent question is: how toxic are nanomaterials at the concentrations at which they may be used? Any toxic effects of nanomaterials will depend on the base material, size, and coatings. To determine and comprehend the toxic effects of nanomaterials, however, correct strategies and interpretation of the data are required, as well as the consideration of assumptions. In nanoparticle toxicity studies, various research teams utilized distinct cell lines, culturing conditions, and incubation periods. With our current understanding of the nature of nanoparticles during toxicity testing, it is difficult to compare results from various research groups and determine whether the observed cytotoxicity is physiologically significant. Currently, a variety of biological models, including cultured cells, aquatic organisms such as embryonic zebrafish (Danio rerio), and whole-animal tests with rodents, are used to determine the potential toxicological effects of chemicals. For many years, diesel and gasoline-powered vehicles and stationary combustion sources have contributed particulate materials of a wide range of sizes, including nanomaterials, to urban atmospheres. The toxic effects of these particles are still being studied, with regulatory concerns shifting away from the traditional particles with aerodynamic diameters of 10 m or less. The results of experiments indicate that particles of finer size are more toxic. To determine and comprehend the toxic effects of nanomaterials, however, correct strategies and interpretation of the data are required, as well as the consideration of assumptions. Nanotechnology products can be divided into a variety of compound classes, including metals, metal oxides, carbon, and semiconductor nanomaterials.

11.4.1 Metal Nanomaterials

Metallic nanoparticles are among the most widely used engineered nanomaterials, but little is known about their environmental fate and effects. Due to the extraordinary properties of nanoscale particles of gold, several groups have investigated the cellular uptake and cellular toxicity of gold nanoparticles [68,69]. It is well known that gold in bulk is safe, but nanoscale particles of gold have unique properties. Chithrani *et al*. [70] investigated the intracellular uptake of colloidal gold nanoparticles of various sizes and shapes. Their findings indicate that kinetics and saturation concentrations are highly dependent on the nanoparticles' physical dimensions, with uptake half-lives of 2.10, 1.90, and 2.24 hours for 14, 50, and 74 nm gold nanoparticles, respectively. Using digestion and subsequent inductively coupled plasma atomic emission spectroscopy measurements, they determined the absolute gold concentrations in cells. They discovered that 50 nm spheres were taken up by cells more rapidly than both smaller and larger spheres in the 10–100 nm range and that spheres were taken up more efficiently than 10–100 nm nanorods. Connor *et al*. [68] analyzed the uptake and potential toxicity of a variety of gold nanoparticles in human leukemia cells. Despite being taken up by human cells, the results indicate that spherical gold nanoparticles with a variety of surface modifiers are not intrinsically toxic to human cells. Our group examined the cellular uptake and cytotoxicity of gold nanomaterials on human skin HaCaT keratinocytes [69,70].

11.4.2 Metal Oxide Nanomaterials

Important industrial materials, metal oxide nanoparticles, are widely used as additives in cosmetics, pharmaceuticals, and food coloring. By applying lotions or creams containing nano-TiO_2 or ZnO as a sunscreen component or fibrous materials coated with nanoscale substances for water or stain repellent properties, the skin is typically heavily exposed to solid nanoparticles. Humans are more likely to be exposed to nanoparticles in the workplace, consumer products, and the environment as the production and use of nanoparticles increase. Several groups have investigated the absorption and toxicity of nanoparticles of metal oxides. Grassian *et al*., [71] reported an inhalation exposure study with nanoparticles of TiO_2 measuring 2–5 nm. They demonstrated that nanoparticles aggregate in the exposure chamber to form aerosol particles with a geometric mean mobility diameter between 120 and 130 nm. Analysis of lung responses in mice following subacute exposure to these aggregates revealed a significant but mild inflammatory response in animals necropsied at week 0, 1, or 2 after the last exposure, with recovery by week 3 post-exposure. Jin *et al*. [72] evaluated the cytotoxicity of different concentrations of homogeneous and weakly aggregated TiO_2 nanoparticles in an aqueous solution using L929 mouse fibroblast cells. Greater concentrations of TiO_2 nanoparticles (>60 g/mL) are associated with a significant increase in oxidative stress. As the concentration of TiO_2 nanoparticles in the culture medium increased, so did the concentrations of reactive oxygen species and lactate dehydrogenase. Park *et al*. [73] reported the cytotoxicity of TiO_2 nanoparticles in BEAS-2B cells cultured in the presence of ROS. They have demonstrated that nanoparticles penetrate the plasma membrane and localize in the peri-region of nuclear membranes, indicating that nanoparticles may have direct interactions with cellular molecules that result in detrimental biological responses in cells. With the induction of reactive oxygen species, the expression of genes related to oxidative stress, such as heme oxygenase-1, or inflammation, such as IL-8, increased.

Nanoparticles have exhibited both positive and negative effects on higher plants, according to the scant phytotoxicity research available. The optimal concentration of TiO_2 nanoparticles has been reported to stimulate photosynthesis and nitrogen metabolism, thereby enhancing the growth of spinach [74,75,76]. Alumina nanoparticles had no negative impact on the growth of California red kidney beans and ryegrass. Nevertheless, it has been reported that they inhibit the root elongation of corn, cucumber, soybean, cabbage, and carrot [75,76,77,78].

High concentrations of ferrophase nanoparticles inhibited the growth of popcorn [79,80]. However, the mechanism of phytotoxicity is still unknown, and there is no information on the potential uptake of nanoparticles by plants and their subsequent fate within food chains. Lin *et al*. (Lin D *et al*., 2008) investigate cell internalization and uptake of ZnO nanoparticles by Lolium perenne (ryegrass). Light, scanning electron, and transmission electron microscopies were used to observe the root uptake and phytotoxicity. In the presence of ZnO nanoparticles, ryegrass biomass decreased significantly, root tips shrunk, and root epidermal and cortical cells were significantly vacuolated or collapsed. However, under ZnO nanoparticle treatments, Zn translocation factors from roots to shoots remained very low.

Using the freshwater alga Pseudokirchneriella subcapitata, Franklin *et al*. [81] compared the toxicity of nanoparticulate ZnO, bulk ZnO, and $ZnCl_2$ to freshwater microalgae. It demonstrated comparable toxicity for nanoparticulate ZnO, bulk ZnO, and $ZnCl_2$, with an IC50 value close to 60 g Zn/mL after 72 hours. L. Cozzoli *et al*. [82] conducted in vitro cytotoxicity tests on a human mesothelioma cell line and a rodent fibroblast cell line using seven industrially significant nanoparticles. In terms of metabolic activity and cell proliferation, the response of cultures exposed to 0–30 ppm nanoparticles (gg1) was compared to that of cultures exposed to non-toxic amorphous silica and toxic crocidolite asbestos. It was discovered that solubility strongly influences the cytotoxic response. The outcome demonstrates a nanoparticle-specific cytotoxic mechanism for uncoated iron oxide, as well as partial detoxification or recovery following treatment with zirconia, ceria, or titania. Reddy *et al*. [82] reported that ZnO nanoparticles are toxic to both gram-negative and gram-positive bacterial systems, *Escherichia col*i (E. coli) and *Staphylococcus aureus* (S. aureus), as well as primary human immune cells. Collectively, their findings demonstrate that ZnO nanoparticles are selectively toxic to various bacterial systems and human T lymphocytes.

Karlsson *et al*. [83] investigated the cytotoxicity and ability to cause DNA damage and oxidative stress of various nanoparticles and nanotubes. The researchers compared the toxicity of metal oxide nanoparticles (CuO, TiO_2, ZnO, $CuZnFe_2O_4$, Fe_3O_4, Fe_3) to that of carbon nanoparticles and multi-walled carbon nanotubes (MWCNT). Their findings demonstrated that the ability of different nanoparticles to cause toxic effects varied considerably. CuO nanoparticles exhibited the highest cytotoxicity and DNA damage. ZnO particles affected both cell viability and DNA damage, whereas TiO_2 particles (a mixture of rutile and anatase) caused only DNA damage. No or low toxicity was observed for iron oxide particles (Fe_3O_4, Fe_2O_3), whereas $CuZnFe_2O_4$ particles were quite effective at inducing DNA lesions. At the lowest dose tested, carbon nanotubes exhibited cytotoxic properties and caused DNA damage. Xia *et al*. [84] reported that TiO_2, ZnO, and CeO_2 induced oxidative stress and cytotoxicity in RAW 264.7 and BEAS-2B cell lines. According to their findings, ZnO induced toxicity in both cells, leading to the production of reactive oxygen species (ROS), oxidant injury, inflammation stimulation, and cell death. In contrast, BEAS-2B and RAW 264.7 cells took up CeO_2 nanoparticles into caveolin-1 and LAMP-1 positive endosomal compartments, respectively, without inflammation or cytotoxicity. CeO_2 also inhibited ROS production and induced cellular resistance to an exogenous source of oxidative stress.

11.4.3. Nanocarbon materials

Carbon nanotubes (CNTs) are emerging as an important new class of multifunctional building blocks for the advancement of nanotechnology due to their one-dimensional hollow nanostructure and unusual properties. Recent advances in nanotechnology have rekindled the pressing need for large-scale CNT production for use in commercial products. The number of industrial-scale facilities for the relatively low-cost production of multi-walled carbon nanotubes (MWCNTs) continues to increase, and consequently, professional and public exposure to MWCNTs is anticipated to increase substantially over the next few years. Several research groups have investigated the absorption and potential toxicity of CNTs, specifically MWCNTs, to humans and other biological systems. CNTs, for example, have been shown to induce inflammatory and apoptotic responses in human T-cells [85,86,87,88,89,90]. Analysis of gene expression revealed that MWCNTs activated human skin fibroblast genes involved in cellular transport, metabolism, cell cycle regulation, and stress response. Magrez *et al*. [91] discovered evidence of cytotoxicity for carbon-based nanomaterials, although MWCNTs were the least toxic of the tested carbon nanotubes, carbon nanofibers, and carbon nanoparticles. In a publication that is somewhat related, Dumortier *et al*. [92] demonstrated that water-soluble CNTs functionalized with polyethylene glycol chains exhibited no toxicity when tested on a variety of immune cells.

Siliva *et al*. [93] demonstrated that ultrafine carbon particles could cross the blood-brain barrier and exert an effect on the central nervous system. Their findings suggest carbon nanoparticles travel from the lungs to the bloodstream, as opposed to releasing clotting agents from the lungs. Given that asbestos fiber inhalation is known to cause asbestosis, lung cancer, and malignant mesothelioma of the pleura; it seems likely that CNTs will also have significant toxic effects on human health due to their structural similarity to asbestos [94-100]. Several studies have demonstrated that CNTs exhibit significant in vitro cytotoxicity, including the induction of oxidative stress, inhibition of cellular proliferation, and induction of apoptosis/necrosis. By instilling a suspension of SWCNT into the lungs of mice, Lam *et al*. [87] determined the effect of single-walled CNT (SWCNT) on lung tissue. According to their findings, SWCNT aggregate into bundles and cause pulmonary inflammation in tandem. Jia *et al*. [93] reported the in vitro cytotoxicity of SWCNTs, MWCNTs, and fullerenes (C60). Their findings indicate that cytotoxicity increases by up to 35% when the dosage of SWCNTs is increased to 11.30 g/cm2. Up to a dose of 226,00 g/cm2 of C60, no significant toxicity was observed. The cytotoxicity appears to follow a mass-based hierarchy: SWCNTs > MWCNTs > quartz > C60.

Zhu *et al*. [101] evaluated the response of mouse embryonic stem (ES) cells to MWCNT-induced DNA damage. Within two hours of exposure, MWNTs were found to accumulate in mouse embryonic stem (ES) cells, induce apoptosis, and activate the tumor suppressor protein p53. In addition, the treatment with MWCNTs increased the expression of two isoforms of the base excision repair protein 8-oxoguanine-DNA glycosylase 1 (OGG1), the double-strand break repair protein Rad 51, the phosphorylation of H2AX at serine 139, and the SUMO modification of XRCC4. Carrero-Sánchez *et al*. [102] compared the toxicological effects of MWCNTs with and without N-doping (CNx). Their findings indicate that when MWCNTs was injected into the trachea of mice, depending on the MWCNT dose, the mice could die from dyspnea. However, CNx nanotubes have never caused a mouse to die. In addition, CNx nanotubes were significantly better tolerated by mice than MWCNTs. Direct administration of extremely high concentrations of CNx nanotubes into the trachea of mice produced only granulomatous inflammatory responses. CNTs have the potential to induce adverse pulmonary effects, including alveolitis, fibrosis, and genotoxicity in epithelial cells, according to Muller *et al*. [103]. The CNTs were intratracheally administered to Wistar rats at a dose of 2 mg/rat to evaluate the short-term response (3 days) in bronchoalveolar lavage fluid. The long-term (60 days) lung response was evaluated biochemically by measuring the lung hydroxyproline content and histologically. Their findings indicate that heating reduces the acute pulmonary toxicity and genotoxicity of CNTs, but grinding restores them, indicating that the intrinsic toxicity of CNTs is primarily mediated by the presence of defective sites in their carbon framework. Chou *et al*. [86] demonstrated that intratracheal administration of 0.5 mg of SWCNTs to 8-week-old male ICR mice induced alveolar macrophage activation, chronic inflammatory responses, and severe pulmonary granuloma formation. Their experimental validation suggests that the uptake of SWCNTs by macrophages can activate numerous transcription factors and activator protein 1. (AP-1).

11.4.4. Quantum Dots

Quantum Dots (QDs) are nanocrystals containing between one thousand and one hundred thousand atoms and displaying unusual "quantum effects" such as prolonged fluorescence. QDs are currently used in the biomedical imaging and electronic industries due to their unique optical and electrical properties. One of the most advantageous characteristics of QDs is their fluorescence spectrum, which makes them ideal fluorophores for biomedical imaging, e.g., fluorescent QDs can be conjugated with bioactive moieties to target specific biologic events and cellular structures, such as labeling neoplastic cells, DNA, and cell membrane receptors [104,105]. Each type of QD has its own unique physicochemical properties, which in turn determines its potential toxicity. As a result, there are discrepancies in the current literature regarding the toxicity of QDs, which can be attributed to a number of factors, including the lack of toxicology-based studies, the variety of QD dosage/exposure concentrations reported in the literature, and the wide variation in physicochemical properties among individual QDs. Importantly, and potentially a source of confusion in assessing QD toxicity, QD toxicity depends on multiple factors derived from both individual QD physicochemical properties and environmental conditions: size, charge, concentration, outer coating bioactivity, and oxidative, photolytic, and mechanical stability have all been identified as determining factors for QD toxicity [106-110].

Zhang *et al*. [111] demonstrated that skin penetration is one of the primary entry points for QDs into biological systems. QD655 and QD565 coated with carboxylic acid were examined for eight and twenty-four hours in flow-through diffusion cells with flexed, tape-stripped, and abraded rat skin to determine if these mechanical actions could perturb the barrier and affect penetration. These findings indicate that the penetration of QD655 and QD565 into intact rat skin is primarily restricted to the uppermost stratum corneum layers. Lovric *et al*. [112] discovered that 10 g/mL of CdTe QDs coated with mercaptopropionic acid (MPA) and cysteamine were cytotoxic to rat pheochromocytoma (PC12) cells in culture. 1 g/mL of uncoated CdTe QDs was cytotoxic. Symptomatic of apoptosis, cell death was characterized by chromatin condensation and membrane blebbing. Trolox, bovine serum albumin (BSA), and N-acetylcysteine were used to determine the effect of QD-induced reactive oxygen species on cell death. Hoshino *et al*. [113] reported that treatment of murine T-cell lymphoma (EL-4) cells with 100 g/mL of QD capping material mercaptoundecanoic acid (MUA) alone (without QD) for 12 hours caused severe cytotoxicity. At 100 g/mL, treatment with cysteamine alone was weakly genotoxic (12 hr). Therefore, their cytotoxicity was attributed to the QD coating rather than the core metalloid complex. Shiohara *et al*. [114] have also observed cytotoxicity induced by QDs. 100 g/mL CdSe/ZnS QDs coated with MUA were found to be cytotoxic to HeLa cells and primary human hepatocytes (MTT assay). Deufus *et al*. [115] determined, using primary hepatocytes as a liver model, that CdSe-core QDs were indeed acutely toxic under certain conditions. They have demonstrated that processing parameters during synthesis, exposure to ultraviolet light, and surface coating can modulate the cytotoxicity of quantum dots. Their findings also suggest that cytotoxicity correlates with the release of free Cd_2+ ions as a result of CdSe lattice degradation. Gopee *et al*. [116) demonstrated that regional lymph nodes, liver, kidney, and spleen are sentinel organs for detecting ID-administered QDs with a PEG coating and a diameter of approximately 37 nm. Regional lymph nodes and liver can be used as sentinel organs to determine the skin penetration of QDs and possibly other nanoparticles, the researchers have concluded. Rouse *et al* (HEK). The cells were treated with QDs at a concentration of 3 nM and a strain of 10% on average. After four hours of cyclic stress, cell viability, QDs uptake, and cytokine production were evaluated. Their findings indicate that the addition of strain increases cytokine production and QDs uptake, leading to irritation and a detrimental effect on cell viability. Mortensen *et al*. (117-123) have demonstrated QDs skin penetration using an in vivo QDs model system. Carboxylated QDs in a glycerol vehicle was applied to the skin of SKH-1 mice with and without UVR exposure. Using tissue histology, confocal microscopy, and TEM with EDAX analysis, the skin collection and penetration patterns were analyzed 8 and 24 hours after QDs application. Both mice not exposed to UVR and mice exposed to UVR demonstrated low levels of penetration. Mice exposed to UVR exhibited significantly higher levels of penetration.

11.5. Limitations of Environmental Nanomaterials

Nanomaterials have superior properties, such as high reactivity and high efficiency, but they have limitations that prevent their widespread environmental applications. The environmental impact of nanomaterials is one of the most pressing issues that must be addressed. There are extensive debates about how the novel properties of nanomaterials could lead to adverse environmental effects with the potential to cause toxicity. The possibility of their release into the environment and subsequent effects on the ecosystem and human health is a growing concern. In addition to the aforementioned dangers, the economic cost of treatment will be affected by the difficulty of nanomaterial regeneration and reuse. The cost has always been a double-edged sword that prevented the global pollution crisis from being resolved. Widespread use has been made of synthesizing nanocomposites of nanomaterials and magnetic nanoparticles with easy separation from water/soil using an external magnetic field. Nonetheless, magnetic nanoparticles and other metal-based nanomaterials may become physiochemically unstable and corrode under harsh environmental conditions, releasing the components and causing secondary pollution. The table below lists additional bottlenecks that are primarily technical and directly related to the nature of nanomaterials. Functionalization of the nanomaterial through the introduction of additional organic or inorganic moieties is an effective method for overcoming the aforementioned disadvantages. Such modifications aid in the regulation of the physicochemical and toxicological properties of nanomaterials and facilitate the incorporation of reactive functional groups on their surfaces, thereby enabling the customization of their functionality for a specific application. Methods for introducing organic functional groups and polymerizing the surface of nanomaterials are discussed. In other sections, the inorganic functionalization is described.

Table 11. 2: Limitations of Environmental Nanomaterials

Nanomaterials	Limitations
Silica-based nanomaterials (mesoporous silica and zeolites)	Limited selectively and adsorption capacity
	Poor recovery
	Weak thermal, chemical, and mechanical stabilities under extensive cycling
	Aggregation
Carbonaceous nanomaterials	Hydrophobicity

	Aggregation (negligible suspension into aqueous solution)
	The low reactivity of carbon
	High cost of carbon nanotubes
	Possible health risks (direct toxicity
	Poor recovery of materials after treatment
Nanoparticles (metals, metal oxides, and quantum dots)	Lack of chemical stability and mechanical strength (corrosion)
	Propensity to aggregate
	Lack of specificity for reactions in complex systems
	Limited selectivity to organics and heavy metals
	Limited activity under visible light (TiO_2, ZnO)
	Fast recombination of photogenerated charge carriers (semiconductor nanoparticles)
	Postrecovery issues

***11.5.1. Effect of Toxicity on Human Health*:**

a) Studies in humans

Epidemiological studies indicate that the ultrafine (nano-sized) fraction of particulate air pollution has a remarkable impact on the aggravation of the cardiorespiratory disease and increased morbidity. Experiments conducted on rodents suggest, on the other hand, that the increased concentration of nanoparticles and higher reactive surface area per unit mass, in addition to their unique chemistry and functionality, play a significant role in the acute and chronic inflammation caused by this exposure. Some animal models have demonstrated that nanoparticles deposited in one organ, such as the lung and gut, can enter the vasculature and target other organs, including the brain and liver [124]. Air pollution epidemiological studies, particularly in occupational environments, have emphasized the significance of worker protection against nanoparticles, including exposure quantification and confounder characterization [125]. The difference between engineered nanoparticles and other nanoparticles is that engineered nanoparticles have been designed for a specific purpose, whereas the other nanoparticles are typically unwanted byproducts of processes such as combustion. Therefore, there is a clear need for epidemiological studies focusing on the effects of ENM on human health. The fact that ENM has only been widely used for a short period of time, with relatively small groups of people exposed to them, has slowed down these efforts, as the number of individuals exposed to ENM has been small, and the duration of exposure has been relatively brief. In 2017, nine epidemiological studies on engineered nanomaterials were published. Among these were a pilot case study [126], seven cross-sectional studies [127-130]. In these studies, workers were exposed to nanosilver [131], MWCNT [132,133] titanium dioxide [134], and a variety of ENM (CNT, silica dioxide, titanium dioxide, nanosilver, and nanoresin) [128], Four of the studies were conducted on a single group of Taiwanese workers [128-131], two on workers in Korea and Czech Republic and one in Russia [132]. Possible differences in safety control at the workplace between Asia and Eastern and Western European nations prevent a generalization of the results. Changes in oxidative stress markers [128-132]; increased levels of several biological markers of inflammation; increased cardiovascular markers [130-131]; and local and systemic markers of pulmonary damage (Fatkhutdinova *et al* Liao *et al.* reported increased symptoms of sneezing and allergic dermatitis as well as changes in lung functional parameters (2014a and 2014b). In contrast, Lee *et al*. found no biochemical or clinical adverse effects in their 2012 pilot study [130].

In the majority of these studies, the levels of exposure were low, but there were exceptions. In addition, the sample size was small, ranging from 2 to 258 workers. On the basis of the available data on worker exposure to engineered nanoparticles, it is too soon to determine whether exposure to engineered nanoparticles is associated with adverse health effects in humans. The currently available studies produce a group with a typically small number of cases, inconsistent and, in some instances, inadequate assessment of exposure, and typically brief intervals between exposure and effect. Nonetheless, it appears that several classes of biomarkers may be influenced by worker exposure to ENM, and this observation should guide future research on the subject. Therefore, current knowledge serves as the foundation for future epidemiological studies.

b) Lessons from ultrafine epidemiological data

Ultrafine particles (UFP) and environmental nanomaterials (ENM) share similar physicochemical properties, but unlike ENM, robust epidemiological data are available for UFP. These data primarily demonstrate an association between UFP exposure and cardio-pulmonary effects; consequently, similar adverse health effects in humans exposed to ENM may be anticipated. In vitro studies indicate that both UFP and ENM can generate reactive oxygen species (ROS) and induce oxidative stress, which is a major factor in the pathogenesis of cardiopulmonary disorders [130-133]. Concerning ENM, the amount of ROS production is likely proportional to their physicochemical properties, with certain materials, such as copper ENM, exhibiting an inherent capacity to produce ROS (Rushton *et al*., 14 of 21 PIETROIUSTI ET AL.

c) Human health implications of experimental studies

Generally speaking, the toxicity of engineered nanomaterials appears to be greater than the toxicity of their chemically identical bulk-size counterparts [133-135]. In fact, the nanometric size of ENM makes them not only chemically more reactive, in part because of their high surface-to-mass ratio, but also able to enter cells and exert their potentially damaging action in locations where larger particles cannot reach [136]. In fact, it has been demonstrated conclusively that nanosized TiO_2 particles induce pulmonary inflammation in the mouse lung more readily than larger, chemically identical TiO_2 particles. Probably because nanoparticles have a much greater surface-to-mass ratio [135]. In addition to these general considerations, there are convincing indications of the toxicity of a number of ENM. Particularly certain types of metal and metal oxide nanoparticles frequently induce inflammation and even genotoxicity, but their potential to induce harmful, permanent morphological changes in their target organ is typically quite limited [136]. However, fibrous materials such as various types of CNT, particularly rigid rod-like CNT, readily induce genotoxicity and have been shown to be carcinogenic to rodents [137]. IARC has classified Mitsui-7 as a possible human carcinogen based on compelling evidence of carcinogenicity from animal experiments [138-139]. It has been hypothesized that other types of CNT are potently immunotoxin and inflammatory, but there is insufficient evidence to support this assertion at this time (National Institute of Occupational Safety and Health, 2013).

On the basis of experimental in vitro and in vivo studies, one can conclude that a number of metal and metal oxide nanomaterials have the potential to cause adverse effects [134]. Several nanometals and nano-sized metal oxides induce oxidative stress, inflammation, and genotoxicity, as an illustration [140]. However, HARN materials stand out as a peculiar group of materials that may be hazardous to human health. Currently, the ability of various methods to predict the toxicity of various materials is extremely limited; therefore, these results must be interpreted with caution. Emerging new approaches utilizing transcriptomics, proteomics, and bioinformatics may offer new opportunities to predict the toxicity of various types of ENM [135]. Before such approaches are fully available, it is necessary to conduct an ENM risk assessment using the current material-by-material method. In addition, the results of the existing epidemiological studies and exposure studies are helpful in putting the results of experimental studies in context. Due to the increasing exposure of workers, consumers, and the environment to various ENM, it is evident that the effects of ENM on humans and the environment will increase; caution is therefore warranted, and possible adverse health effects of ENM should be closely monitored. Simultaneously, actions toward setting various exposure limits, especially OEL, are a topic of great relevance. Recent emphasis has been placed on the fact that ENM safety is a global issue, as the demand for ENM-based technologies and products has increased steadily [136-143]

11.6.Future Scope of Environmental Nanomaterials

Nanotechnology is regarded as the technology with the most rapid growth in the current decade [144]. The invention of instruments, such as scanning tunneling microscopy, electron microscopy, etc. that allows scientists to investigate the matter at the nanoscale level, then synthesize, characterize, and manipulate nanoscale materials [145] is likely the cause of this explosive growth. According to scientists and businesspeople, intelligent nanomaterials have the potential to revolutionize nearly every aspect of contemporary life. They view it as the most appropriate technology for the modern world due to its economic potential, ability to develop optimized products, and, most importantly, its potential to reduce pressure on resources and environmental stress. Anticipating the future of nanotechnology, it is evident that it will provide many more applications with added value [145, 146] and lead to the development of new diagnostic tools and industries, such as nanoenergy, nanofood, nanoagriculture, nanomedicine, nanobiotechnology [146], and nanoelectronics [147]. In addition, it will provide solutions to industrial problems and assistance to other technologies, such as biotechnology, physics, computer sciences, psychology, and other scientific fields, allowing them to grow and develop at an unprecedented rate. Additionally, the convergence nature of nanotechnology will bring sustainability to all facets of our lives [148]. It will unlock opportunities for nanoscale engineering [149] and miniaturize physical technologies, bring innovative therapeutic inventions, and improve environmental monitoring and safety, 34 Muhammad Irfan Sohail and others. Optimizing production processes and improving qualities [144]. The developments in nanotechnology also promise a commercial revolution by facilitating future improvements in product designs, specifications, and manufacturing [149-151]. Since the inception of nanotechnology in 1960, its popularity among technological researchers and scientists has resulted in the development of multiple platforms for nanomaterials research, the publication of approximately 2 million research articles, and the creation of 1 million registered applications [151] while advancing at a rate of 10% per year [152]. According to many futurists, our knowledge about the environmental and human health implications of this technology lags far behind where it ought to be right now [153]. Nanotechnology is well-suited to addressing the convergent nature of problems in the current century.

Nanotechnology is creating new products, enhancing the quality of life, and advancing techniques. Nanotechnology generates nanomaterials that are smaller, sleeker, stronger, faster, safer, and more dependable [154,155]. As new applications for nanomaterials with these unique properties are identified, the number of products containing these nanomaterials and their potential applications continue to increase. Environmental applications such as medical, agricultural, industrial, electrical, and cosmetic products can benefit from ENPs. These nanoparticles consist of a vast array of metal NPs, the most widely used of which are nanogold in Hyperthermia Cancer Therapy [HCT), diagnostics for heart and infectious diseases, sensors and electronics, and nanosilver as antimicrobial agents in food packaging. In the medical field, drug delivery ENPS is utilized in DNA transfecting agents, hydrogels, DNA chips, and as therapeutic agents for prion diseases. They are utilized extensively in diagnostic tools and solar batteries. Nanomaterials are utilized in the production of agriculture input fertilizers/pesticides for pest control and efficient fertilizer distribution[156-157]. In the chemical industry, gold nanoparticles are used as a catalyst for certain oxidation reactions and fuel cells. Single-walled carbon nanotubes (SWCNT) have superior thermal and electrical conductivity and tensile strength. SWCNT has a strength-to-weight ratio of 460 times greater than steel. CNT and CNT derivatives have applications in the plastics, automotive, and aerospace industries due to their tensile strength. Burning, dry and wet drilling of polymer and abrasion and sanding of epoxy resins and automobile parts release CNTs into the environment [169]. In the paint industry, metal oxide

NPs such as titanium dioxide (TiO_2), zinc oxide (ZnO), Silicon oxide (SiO_3), Aluminium oxide (Al_2O_3), as well as elemental Silver (Ag) and Tin (Sn), is utilized. Due to their unique ability to block ultraviolet radiation, titanium-based nanoparticles (TiO_2) are utilized in solar cells, sunscreens, cosmetics, and bottle coatings. Various semiconductor nanoparticles, such as Cd-Se, Cd-Te, Cd-Se-Te, In-P, Zn-Se, Zn-S, Bi_2S_3, etc., play an important role in the industrial and electronic business. Nanoparticles of ZnO, SiO_2, and Ag are utilised in the cosmetics and coatings industries. These NPs are applied in chemical and physical fields, including microcapsules, nanolatex, coloured glasses, chemical sensors, modified electrodes, and are released into the environment via industrial wastes [170-174] due to their unique properties.

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