Nanotechnology for Air and Land Pollution

Santosh S. Chobea\*, Manohar K. Zateb, Tulshidas S. SavaleC, Savita M. MathureC Charushila K.

Nerkara and Dyandevi M. Mathured Arvind M Patil, Ratnnadeep C. Sawantf

a\*Organic Research Laboratory, P. G. Department of Chemistry, L.V.H Arts, Science and Commerce College, Nashik (M.S.) India

bSVKT Arts, commerce & Science College, Deolali Camp, Nashik

COrganic Research Laboratory, P. G. Department of Chemistry, M.S.G. Arts, Science and Commerce College, Malegaon, Nashik (M.S.) India

dBharati Vidyapeeth (Deemed To Be University), Poona College Of Pharmacy, Erandwane,

Pune- 411038

eSNJB's KKHA Arts, SMGL Commerce and SPHJ Science College Chandwad Dist Nashik

fDepartment of Chemistry, Dr. Ambedkar College, Deekshabhoomi, Nagpur-440010 (MS) India

# Corresponding Author: [chobess222@gmail.com](mailto:chobess222@gmail.com)

**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 air pollution rectification, 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. Reducing the release of industrialized hazardous waste and other toxins can help with this. Higher electrical conductivity, higher strength-to-weight ratios, and dramatically enhanced surface areas and reactivities are only a few of the extraordinary and advantageous characteristics of nanomaterials. 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; nanosensors;

# Introduction

Unintended emissions of gases, particles, and aerosols into the inferior atmosphere are referred to as air pollution. [1]. such pollution is due to both sources viz; artificial and natural (such as wind- borne dust, volcanic eruptions, and forest fires). The gases and particles that pollutes the air results in risk to human health. Nitrogen oxides, sulphur oxides, hydrogen sulphides, small powder particles (aerosols), and volatile organic compounds are the most common types of air contaminants (VOCs). According to the World Health Organization (WHO), lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, stroke, and acute respiratory infections are among the seven million people who die each year from the combined effects of interior and outside air pollution. 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, there is significant risk to health and climate. For the purpose of environmental protection from adverse effects of pollution, a number of nations have enacted legislation regulating numerous pollution groups and justifying their adverse effects. At the nanoscale use of science, engineering, and technology, which ranges from one to one hundred nanometers, is known as nanotechnology. In general, nanotechnology, which often refers to structures with dimensions of 100 nm or less, involves the creation of substances and devices that fit inside this size range. Nanotechnology is incredibly diverse, ranging from completely new methods based on molecular self-assembly for the creation of nanoscale-sized sophisticated materials for the development of nanoscale-sized advanced materials. It is also feasible to directly influence matter using nanotechnology at the atomic level.

Recent research has focused on nanotechnology's potential to offer innovative clarifications to succeed and decrease pollution in water, air, and land, along with improvement in performance of conventional remediation practices. 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 skills for cleaning air pollution, catalysis, pollution detection, and other applications. Many reviews have established that nanoparticles are used in diverse areas and that they have an effect on the environment. Nanomaterials are a great way to stop pollution by reducing the amount of industry waste and other contaminants that are released into the environment due to their unique properties and characteristics. Nanomaterials' exceptional and advantageous properties include significantly greater reactivity and surface area, greater electrical conductivity, and increased ratio of strength-weight. Nanotechnology and nanomaterials are the best way to find and treat small amounts of pollution in the world. The current chapter involves the use of several nanomaterials in the remediation of contamination of air.

The current study involves the investigation of nanomaterials in sense of nanoadsorbents, nanocatalysts, nanofilters, and nanosensors. Various nanostructures, including nanoparticles, nanofibers, nanorods, nanosheets, and nanowires, have been stated for use in air purification. We primarily investigate materials based on carbon 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.

## 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 economical technology for modification of environmental concerns. Titania is significantly changed using metallic and non-metallic dopants to increase its catalytic activity even more. The Novel catalyst, numerous types such as WO3 decorated ZnO, was further included in 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 [3].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 [4]

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 [5]. Toxic volatile organic compounds (VOCs) and fine particulate matter (PM2.5) in indoor air constitute a hazard to strength of human being, including cancer, leukemia, fetal malformation, and abortion. As a result, developing technology to reduce inside contamination of air is critical to circumvent 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.[6]

## 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 [7] 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 [8]. 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 [9], adsorption [10], catalytic oxidation [11], disinfection, and sensing [12] 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 [13]. First, nanoparticles tend to agglomerate in a fluidized system or a stiff substrate, resulting in significant activity loss and pressure decrease [14]. 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. [15] 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 [16] 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 [17].

## 1.2.1 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 [18]. 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 [19]. By adding functional nanoparticles to the membrane, scientists were able to make nanocomposite membranes with advanced features. This new class of membranes had better mechanical or thermal stability, porosity, and hydrophilicity, such as higher permeability, anti-fouling, antibiotic, adsorbent, or photocatalytic properties. [20]. Currently, adsorption and separation nanotechnology are near maturity.

## 1.2.2 Catalysis

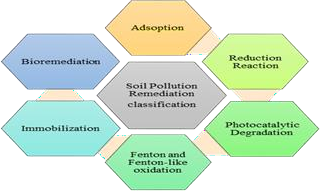
To eliminate trace contaminants and microbiological pathogens from water, the advanced oxidation process of catalytic or photocatalytic oxidation is applied. It’s a better initiative to make both contaminants biodegradable form non-biodegradable components [21]. Organic molecules are being polished by photolysis [22]. High surface to volume ratio of nanocatalysts showed better catalytic performance than bulkier equivalents. Size-dependent behavior was observed 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 [23]. The immobilizing of nanoparticles onto diverse substances improved the nanocatalyst stability, and the resulting nanocomposites were suitable for contemporary photo-reactors [24].

## 1.2.3 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 [25]. 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). [26]. 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. [27]. 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. [28].

## Nanotechnology for degradation of land waste

Nanotechnology can be applied to contaminated soil, in which pollutants viz; 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 [29-30]. 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 [31]. In a simultaneous adsorption and oxidation scenario, the presence of ENMs could facilitate both adsorption and redox degradation of micropollutants [32]. 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



**Fig. 1.** Soil Pollution Remediation Classification

on heavy metals and organic compounds such as carbon nanomaterials, metal oxides Fe3O4, 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, Fe2O3, cerium oxide, Al2O3, MnxOy, TiO2,and MgO shows the good result for soil remediation [33]. Recently magnetic nanosized adsorbents have been used for removing magnetic impurities from soil [34]. 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. [34-37]. 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 [38]. 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 environment with plastic garbage can have major consequences for living forms, ecosystems, and the economy. Additionally, plastic trash can degrade into tiny particles known as microplastics (MPs) and neoplastic (NPs), resulting in environment and living beings collabortaion. 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 [39-41]. 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 [42]. Different enzymes have also been immobilized on inorganic nanostructures. For instance [43] Covalent bonding immobilized lipase and cutinase on SiO2 nanoparticles and Fe3O4@SiO2 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 [44].

## Nano-Particles as adsorbent

Advanced nano adsorbents are much better at removing gases, bacteria, and other organic molecules from the environment than traditional adsorbents, which are not very effective and have a small amount of active site surface area. Adsorption mainly depends on adsorbent properties viz; porosity and surface area.

The adsorbents viz; Carbon-based materials like CNTs, activated carbon, and carbon fiber composites are more likely to attract CO2 [45]. Recently, there has been more interest in using CNTs to absorb CO2 because they are reversible. When the temperature goes up, the CO2 can be taken away from the CNTs by desorption. Amine-functionalized CNTs acts as promising way to capture CO2. CNT is a good support for adsorbents because it has a larger surface area and is chemically stable. This makes it less likely that the adsorbent will lose its structure during the CO2 absorption process. In a study by [46], better CO2 adsorbents were made by amine-functionalizing multi-walled CNTs with (3-aminopropyl) triethoxysilane in two steps: acid pretreatment with sulfuric acid and nitric acid, then amine-functionalization with (3-aminopropyl)triethoxysilane. The amine-functionalized multi-walled CNTs performed better in the CO2 adsorption test, play a vital role in CO2 uptake of 75.40 mg CO2 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. Because zinc oxide nanoparticles are stable at high temperatures for the non-catalytic suffixation reaction [47], they are being studied closely as a way to clear the air of hydrogen sulfide, especially at higher temperatures through an adsorption process. [48] They talked about a simple, one-step method for making ZnO nanoparticles that doesn't use surfactants and heat processes afterward. The nanoparticles can be used to remove H2S from the air. The adsorption tests outcomes confirmed that the prepared zinc oxide . Nano adsorbent had a greater capacity for hydrogen sulphide adsorption due to the enhanced treatment of air volume and more adsorption time. The aforementioned study proved that the prepared zinc oxide Nano adsorbent is a particularly promising component for various ecological applications. SO2 is an odorless, nonexplosive, and noncombustible gas that can impart a taste to the air at concentrations between 0.30 and 1.0 ppm. Atmospherically, SO2 will transform into extremely stable byproducts. SO2 is emitted into the atmosphere by the combustion of sulfur- containing fossil fuels and other industrial processes [49-50] reported results from single gas adsorption, confirming that zeolites are highly effective at removing CO2, SO2, and nitric oxide [51]. established that iron nanoparticles with a size of approximately 3–4 nm enhanced the adsorption capacity of SO2 by 80% through dispersed reactive centers. Sekhavatjou et al. [52] observed how nanoparticles of zinc oxide and iron oxide could be used to separate sulphur components from sour gas. Mahmoodi Meimand *et al* [53] investigated how clinoptilolite zeolite with iron oxide nanoparticles and natural clinoptilolite zeolite could be used as nano adsorbents for SO2. Due to the regenerative nature of the iron oxide nanoparticles, the modified zeolite with iron oxide nanoparticles exhibited greater SO2 absorption efficiency than the unmodified zeolite. This could be considered an effective, trustworthy, and practical method for removing SO2 from the air. Many researchers [54] on the use of MOFs as nanoadsorbents for removing nitrogen and sulphur from gas streams have been published. Among these MOF-based nanoadsorbents, NH2-substituted UiO-66 exhibited a greater acid gas (e.g.,CO2, H2S, NO2, and SO2) adsorption capacity. UiO-66-NH2 has the capability of adsorbing noxious gases in a matter of minutes, making it a potential material for detoxification. UiO-66- NH2 is a great material for acid gases removal owing to its different size pores, more holes and higher concentration.

# Table 1: Nano adsorbents based on Carbon for environmental contaminants removal

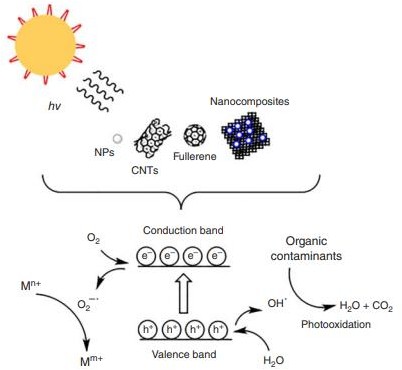
|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Nano adsorbent** | **Contaminants** | **Sorption capacity** | **pH** | **Time** | **Kinetics** | **Isotherm models** | **References** |
| MWCNT-TYR | Methylene blue | 440 mg/g | 6 | 7 | Pseudo- second order kinetic | Langmuir isotherm model | 56 |
| MWCNTs(5–  15nm) | Pb(II)  Ni(II) | 215.38±0.0  3 mg/g  230.78±0.0  1 mg/g | 5 | 60 | Pseudo- second order kinetics | Langmuir isotherm model | 57 |
| AminMag MWCNTs@Si O2 | Pb(II)  Cd(II) | 98–104% | 8 | 5 | Pseudo- second order kinetics | Langmuir isotherm model | 58 |
| Single-walled carbon nanotubes magnetic nanoparticles (SWCNT-MN)  hybrid  adsorbent | Xyline | 50 mg/g | 8 | 20 |  | Langmuir  –  Freundlic h(GLF)  isotherm | 59 |
| Nitrogen-doped graphene oxide nanosheets (N- GO) | Congo red | 98–99% | 2 | 360 | Pseudo- second order kinetics | Langmuir isotherm model | 60 |
| Graphene oxide | Basic red 46 | 370.4mg/l | 11 | 30 | Pseudo- second order kinetics | Langmuir isotherm model | 61 |

## Nano-Particles as catalysts

Nano-based photocatalysis is a possible way to purify pollutants in the air, and researchers have been looking into it more in recent year. Photocatalysis can be used to clean water, clean the air, and clean up polluted water, among other things. This is because it is better at turning photon energy into chemical energy, which is needed to quickly break down and mineralize persistent environmental pollutants. [62]. The separation efficacy of air contaminants is affected by the phase structure, texture of surface and nano based analysis of photocatalyst. 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 [63]. Photocatalysis with modified TiO2 has the potential to enhance both air quality and health. Smart coatings, which are standard materials suitable for interior applications, are produced by modified TiO2 by means of innovative photocatalytic properties below 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 TiO2 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. Under controlled lighting, temperature, and humidity settings, the ability of paints with TiO2 in them to separate nitric oxide is tested. On subsequent mineralization of substrates of inorganic and organic origin, photocatalysts based on titania have the potential to eradicate a vast array of microbes [64]. Binas et al. [65-66] showed that it is possible to separate NOx gases and VOCs in normal amounts of outdoor or indoor air using a photocatalytic method based on titania. In recent years, there has been a lot of interest in titania-based photocatalysts as disinfectants for a wide range of germs, including those that stay in the environment for a long time, like 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. looked into how gaseous formaldehyde breaks down when light hits nanoparticles of zinc oxide on bone char. Based on the results of the tests, the most formaldehyde could break down was about 73%. The findings showed that putting ZnO nanoparticles on bone char makes photocatalytic breakdown work better. This is because formaldehyde molecules stick to bone char better, which makes it easier for them to move to the catalytic zinc oxide and leads to a high photocatalytic rate. Vohra et al. [67] made a photocatalyst made of silver-ion-doped titania that kills microorganisms in the air better. In an experiment with moving air, a catalyst-coated filter is used to check how well a silver-ion-doped photocatalyst works. 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. Researchers found that this improved photocatalyst was one order of magnitude better at killing microorganisms than a normal photocatalyst made of titania. This improved photocatalysis process is effective against higher amounts of microorganisms in the air. This makes it a good option for protecting against bioterrorism.

## 1.3.3 Organic Contaminants Deduction by means of nanotechnology:

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. Through a process called photocatalytic breakdown, the organic pollutants can be turned into carbon dioxide and water. Organic paints made by factories are another major source of organic pollution. Through a process called photocatalysis, certain metal ions can break down these colors. Figure 1. illustrates the photocatalytic degradation of metal and organic contaminants.



**Fig. 1.** metal and organic contaminants degradation mechanisms

Source: Guerra *et al*.[68] /MDPI/Licensed under CC BY 4.0.

# 1.4. Future Scope of Environmental Nanomaterials

Nanotechnology is regarded as the technology with the most rapid growth in the current decade [69]. Most likely, this rapid growth is due to the invention of instruments, like scanning tunneling microscopy, electron microscopy, etc., that allows scientists to study matter at the nanoscale level, then synthesize, describe, and change nanoscale materials [70]. Scientists and businesspeople say that intelligent nanomaterials have the ability to change almost every part of modern life. They think it is the best technology for the modern world because of its economic potential, its ability to make better goods, and, most importantly, its ability to reduce stress on resources and the environment. When we look to the future of nanotechnology, it is clear that it will have many more useful applications [71] and lead to the creation of new diagnostic tools and industries, such as nanoenergy, nanofood, nanoagriculture, nanomedicine, nanobiotechnology [72], and nanoelectronics. [73]. It will also help solve problems in industry and help other technologies like biology, physics, computer science, psychology, and other scientific fields grow and develop at an unprecedented rate. Nanotechnology will also make all parts of our lives more sustainable because of its convergence nature [74].

It will open doors for nanoscale engineering [75] and make physical technologies smaller. It will also lead to new therapeutic inventions and better tracking and safety in the environment, Muhammad Irfan Sohail and others. Optimizing production processes and improving qualities . Nanotechnology's progress could also lead to a business revolution by making it easier to improve product designs, specs, and manufacturing. [76-77]. Since nanotechnology was invented in 1960, it has become popular among technological researchers and scientists. This has led to the creation of multiple platforms for nanomaterials research, the publication of about 2 million research articles, and the creation of 1 million registered applications, all while progressing at a rate of 10% per year. [78]. Many futurists say that we don't know nearly as much as we should about how this technology will affect the world and people's health [79]. Nanotechnology is a good way to solve problems that are related to each other in this century.

Nanotechnology is making new things, making life better, and making methods better. Nanotechnology makes nanoparticles that are smaller, smoother, stronger, faster, safer, and more reliable. [80-81]. As new applications to use nanomaterials with these unique properties are found, the number of goods that contain them and the number of ways they can be used keeps growing. ENPs are good for the environment and can be used in medical, agricultural, industrial, electrical, and cosmetic items. These nanoparticles are made up of many different types of metal NPs. Nanogold is used in Hyperthermia Cancer Therapy [HCT], diagnostics for heart and infectious diseases, sensors and electronics, and nanosilver is used in food packing as an antimicrobial agent. In the medical field, drug delivery ENPS is used in DNA transfecting agents, hydrogels, DNA chips, and as a treatment for prion illnesses. There are a lot of diagnostic tools and solar packs that use them. Nanomaterials are used to make fertilizers and poisons, which help get rid of pests and get the fertilizer to where it needs to be[82-84]. Gold nanoparticles are used as a catalyst in the chemical industry for some oxidation processes and fuel cells. Single-walled carbon nanotubes (SWCNT) are better at conducting heat and electricity and being pulled apart. SWCNT is 460 times stronger than steel for how much it weighs. Due to their tensile strength, CNT and materials made from it are used in the plastics, car, and aerospace industries. CNTs are released into the environment when polymers are burned, drilled dry or wet, or when epoxy resins and car parts are worn down or sanded. [85]. Metal oxide nanoparticles (NPs) are used in the paint industry. These include titanium dioxide (TiO2), zinc oxide (ZnO), silicon oxide (SiO3), aluminum oxide (Al2O3), and even pure silver (Ag) and tin (Sn). Titanium-based nanoparticles (TiO2) are used in solar cells, sunscreens, makeup, and bottle coatings because of their unique ability to block UV light. Semiconductor nanoparticles like Cd-Se, Cd-Te, Cd-Se-Te, In-P, Zn-Se, Zn-S, Bi2S3, etc. are very important in the industrial and technology business. In the cosmetics and coatings businesses, ZnO, SiO2, and Ag nanoparticles are used. Due to their unique qualities, these NPs are used in chemical and physical fields, such as microcapsules, nanolatex, colored glasses, chemical sensors, and modified electrodes. They are also released into the environment through industrial wastes [86-99].

# References

1. Feynman, R.P. (1960). There’s plenty of room at the bottom. Caltech Engineering and Science, February 1960. This is a transcript of Feynman’s talk given on December 29. 1959 at the Annual Meeting of the American Physical Society.
2. Nikolova, M.P. and Chavali, M.S. (2020). Metal oxide nanoparticles as biomedical materials. Biomimetics 5 (2): 27.
3. Nema, A., Kaul, D. S., Mukherjee, K., & Jeyaraman, J. D. (2022). Photo-active catalysts in building and construction materials for air pollution treatment: A bibliometric analysis. Materials Today: Proceedings.
4. Daglar, H., Altintas, C., Erucar, I., Heidari, G., Zare, E. N., Moradi, O., & Sillanpa,

M. (2022). Metal-organic framework-based materials for the abatement of air pollution and decontamination of wastewater. Chemosphere, 135082.

1. Cheng, Y., Wang, W., Yu, R., Liu, S., Shi, J., Shan, M., ... & Deng, H. (2022). Construction of ultra-stable polypropylene membrane by in-situ growth of nano-metal– organic frameworks for air filtration. Separation and Purification Technology, 282, 120030.
2. Yue, X., Ma, N. L., Sonne, C., Guan, R., Lam, S. S., Van Le, Q., & Peng, W. (2021). Mitigation of indoor air pollution: A review of recent advances in adsorption materials and catalytic oxidation. Journal of hazardous materials, 405, 124138.
3. Qin, G., Niu, Z., Yu, J., Li, Z., Ma, J., & Xiang, P. (2021). Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. Chemosphere, 267, 129205.
4. Kumar, S., Islam, A. R. M. T., Islam, H. T., Hasanuzzaman, M., Ongoma, V., Khan, R., & Mallick, J. (2021). Water resources pollution associated with risks of heavy metals from Vatukoula Goldmine region, Fiji. Journal of environmental management, 293, 112868.
5. Nain, A., Sangili, A., Hu, S. R., Chen, C. H., Chen, Y. L., & Chang, H. T. (2022). Recent progress in nanomaterial functionalized membranes for removal of pollutants. Iscience, 104616.
6. Ruhaimi, A. H., Hitam, C. N. C., Aziz, M. A. A., Hamid, N. H. A., Setiabudi, H. D., & Teh, L. P. (2022). The role of surface and structural functionalisation on graphene adsorbent nanomaterial for CO2 adsorption application: Recent progress and future prospects. Renewable and Sustainable Energy Reviews, 167, 112840.
7. Liu, D., Jiang, P., Xu, X., Wu, J., Lu, Y., Wang, X., ... & Liu, W. (2022). MOFs decorated sugarcane catalytic filter for water purification. Chemical Engineering Journal, 431, 133992.
8. Liu, X., Yao, Y., Ying, Y., & Ping, J. (2019). Recent advances in nanomaterial-enabled screen-printed electrochemical sensors for heavy metal detection. TrAC Trends in Analytical Chemistry, 115, 187-202.
9. Shukla, S., Khan, R., & Daverey, A. (2021). Synthesis and characterization of magnetic nanoparticles, and their applications in wastewater treatment: A review. Environmental Technology & Innovation, 24, 101924
10. Zeng, M., Chen, M., Huang, D., Lei, S., Zhang, X., Wang, L., & Cheng, Z. (2021). Engineered two-dimensional nanomaterials: An emerging paradigm for water purification and monitoring. Materials Horizons, 8(3), 758-802
11. Zahid, M., Nadeem, N., Tahir, N., Majeed, M. I., Naqvi, S. A. R., & Hussain, T. (2020). Hybrid nanomaterials for water purification. In Multifunctional hybrid nanomaterials for sustainable agri-food and ecosystems (pp. 155-188). Elsevier.
12. Saleh, T. A. (2017). An overview of nanomaterials for water technology. Advanced Nanomaterials for Water Engineering, Treatment, and Hydraulics, 1-12.
13. Ahuja, S. (2021). Select applications of nanomaterials for water purification. In Handbook of Water Purity and Quality (pp. 339-357). Academic Press.
14. Mohamed, M. B. (2011). Low cost nanomaterials for water desalination and purification. United Nations UNSCO.
15. Li, Q., Mahendra, S., Lyon, D. Y., Brunet, L., Liga, M. V., Li, D., & Alvarez, P. J. (2008). Antimicrobial nanomaterials for water disinfection and microbial control: potential applications and implications. Water research, 42(18), 4591-4602
16. Nasrollahzadeh, M., Sajjadi, M., Iravani, S., & Varma, R. S. (2021). Green-synthesized nanocatalysts and nanomaterials for water treatment: Current challenges and future perspectives. Journal of hazardous materials, 401, 123401.
17. Yu, M., Shang, C., Ma, G., Meng, Q., Chen, Z., Jin, M & Zhou, G. (2019). Synthesis and characterization of mesoporous BiVO4 nanofibers with enhanced photocatalytic water oxidation performance. Applied Surface Science, 481, 255-261.
18. Lee, C. H., Tiwari, B., Zhang, D., & Yap, Y. K. (2017). Water purification: oil–water separation by nanotechnology and environmental concerns. Environmental Science: Nano, 4(3), 514-525.
19. Santhosh, C., Velmurugan, V., Jacob, G., Jeong, S. K., Grace, A. N., & Bhatnagar, A. (2016). Role of nanomaterials in water treatment applications: a review. Chemical Engineering Journal, 306, 1116-1137.
20. Singh, K. K., Singh, A., & Rai, S. (2022). A study on nanomaterials for water purification. Materials Today: Proceedings, 51, 1157-1163.
21. Zhu, Y., Liu, X., Hu, Y., Wang, R., Chen, M., Wu, J., ... & Zhu, M. (2019). Behavior, remediation effect and toxicity of nanomaterials in water environments. Environmental research, 174, 54-60.
22. Teow, Y. H., & Mohammad, A. W. (2019). New generation nanomaterials for water desalination: A review. Desalination, 451, 2-17.
23. Gopakumar, D. A., Pai, A. R., Pasquini, D., Ben, L. S. Y., HPS, A. K., & Thomas, S. (2019). Nanomaterials—state of art, new challenges, and opportunities. Nanoscale Materials in Water Purification, 1-24.
24. Botes, M., & Eugene Cloete, T. (2010). The potential of nanofibers and nanobiocides in water purification. Critical reviews in microbiology, 36(1), 68-81.
25. Liu, C., Lin, H., Li, B., Dong, Y., & Yin, T. (2020). Responses of microbial communities and metabolic activities in the rhizosphere during phytoremediation of Cd-contaminated soil. Ecotoxicology and Environmental Safety, 202, 110958.
26. Bajpai, A., Atoliya, N., & Prakash, A. (2022). Genetically engineered microbes in micro- remediation of metals from contaminated sites. In Current Developments in Biotechnology and Bioengineering (pp. 397-416). Elsevier.
27. Wang, L., Huang, Y., Xu, H., Chen, S., Chen, H., Lin, Y., ... & Huang, X. (2022). Contaminants-fueled laccase-powered Fe3O4@ SiO2 nanomotors for synergistical degradation of multiple pollutants. Materials Today Chemistry, 26, 101059.
28. Qian, Y., Qin, C., Chen, M., & Lin, S. (2020). Nanotechnology in soil remediation− applications vs. implications. Ecotoxicology and Environmental Safety, 201, 110815.
29. Vittori Antisari, L., Carbone, S., Gatti, A., Vianello, G., & Nannipieri, P. (2015). Uptake and translocation of metals and nutrients in tomato grown in soil polluted with metal oxide (CeO2, Fe3O4, SnO2, TiO2) or metallic (Ag, Co, Ni) engineered nanoparticles. Environmental Science and Pollution Research, 22(3), 1841-1853.
30. Shen, H., Chen, J., Dai, H., Wang, L., Hu, M., & Xia, Q. (2013). New insights into the sorption and detoxification of chromium (VI) by tetraethylenepentamine functionalized nanosized magnetic polymer adsorbents: mechanism and pH effect. Industrial & Engineering Chemistry Research, 52(36), 12723-12732.
31. Wang, C.-B., Zhang, W.-X., 1997. Synthesizing nanoscale iron particles for rapid and complete dechlorination of TCE and PCBs. Environmental Science & Technology 31, 2154e2156.
32. Lien, H., Zhang, W.-X., 1999. Transformation of chlorinated methanes by nanoscale iron particles. Journal of Environmental Engineering 125, 1042-1047.
33. Zhang, W.-X., 2003. Nanoscale iron particles for environmental remediation: an overview. Journal of Nanoparticle Research 5, 323-332.
34. Song, H., Carraway, E.R., 2005. Reduction of chlorinated ethanes by nanosized zero- valent iron: kinetics, pathways, and effects of reaction conditions. Environmental Science & Technology 39, 6237-6245.
35. Jawed, A., Saxena, V., & Pandey, L. M. (2020). Engineered nanomaterials and their surface functionalization for the removal of heavy metals: A review. Journal of Water Process Engineering, 33, 101009.
36. Cárdenas-Alcaide, M. F., Godínez-Alemán, J. A., González-González, R. B., Iqbal, H. M., & Parra-Saldívar, R. (2022). Environmental impact and mitigation of micro (nano) plastics pollution using green catalytic tools and green analytical methods. Green Analytical Chemistry, 100031
37. Kaushal, J., Khatri, M., & Arya, S. K. (2021). Recent insight into enzymatic degradation of plastics prevalent in the environment: A mini-review. Cleaner Engineering and Technology, 2, 100083
38. Krakor, E., Gessner, I., Wilhelm, M., Brune, V., Hohnsen, J., Frenzen, L., & Mathur, S. (2021). Selective degradation of synthetic polymers through enzymes immobilized on nanocarriers. MRS Communications, 11(3), 363-371.
39. Wei, X., Chen, H., Lin, D., Xu, H., Wang, J., Zhang, J. & Zhang, Y. (2022). A field study of nano-FeS loaded lignin hydrogel application for Cd reduction, nutrient enhancement, and microbiological shift in a polluted paddy soil. Chemical Engineering Journal, 138647.
40. Xu, X., Song, C., Miller, B.G., and Scaroni, A.W. (2005). Influence of moisture on CO2 separation from gas mixture by a nanoporous adsorbent based on polyethylenimine- modified molecular sieve MCM-41. Industrial and Engineering Chemistry Research 44: 8113–8119.
41. Gui, M.M., Yap, Y.X., Chai, S.P., and Mohamed, A.R. (2013). Multi-walled carbon nanotubes modified with (3-aminopropyl) triethoxysilane for effective carbon dioxide adsorption. International Journal of Greenhouse Gas Control 14: 65–73.
42. Portela, R., Rubio-Marcos, F., Leret, P. et al. (2015). Nanostructured ZnO/sepiolite monolithic sorbents for H2S removal. Journal of Materials Chemistry A 3 (3): 1306– 1316.
43. Huy, N.N., Thuy, V.T.T., Thang, N.H. et al. (2019). Facile one-step synthesisof zinc oxide nanoparticles by ultrasonic-assisted precipitation method and itsapplication for H2S adsorption in air. Journal of Physics and Chemistry of Solids 132: 99–103.

**[48]** Liu, Z., Mao, X., Tu, J., and Jaccard, M. (2014). A comparative assessment of economic- incentive and command-and-control instruments for air pollutionand CO2 control in China’s iron and steel sector. Journal of Environmental Management 144: 135–142.

**[49]** Luo, L., Guo, Y., Zhu, T., and Zheng, Y. (2017). Adsorption species distribution and multicomponent adsorption mechanism of SO2, NO, and CO2 on commercial adsorbents. Energy & Fuels 31 (10): 11026–11033.

**[50]** Arcibar-Orozco, J.A., Rangel-Mendez, J.R., and Bandosz, T.J. (2013). Reactive adsorption of SO2 on activated carbons with deposited iron nanoparticles. Journal of Hazardous Materials 246: 300–309.

**[51]** Huang, Y., Wang, W., Zhang, Y. et al. (2019). Synthesis and applications of nanomaterials with high photocatalytic activity on air purification. In: Novel Nanomaterials for Biomedical, Environmental and Energy Applications (ed. X. Wang and X. Chen), 299–325. Elsevier

**[52]** Sekhavatjou, M.S., Moradi, R., Hosseini, A.A., and Taghinia, H.A. (2014). A new method for sulfur components removal from sour gas through application of zinc and iron oxides nanoparticles. International Journal of Environmental Research (IJER) 8 (2): 273– 278.

**[53]** Mahmoodi Meimand, M., Javid, N., and Malakootian, M. (2019). Adsorption of sulfur dioxide on clinoptilolite/nano iron oxide and natural clinoptilolite. Health Scope 8 (2): 1– 8.

**[54]** Li, Z., Liao, F., Jiang, F. et al. (2016). Capture of H2S and SO2 from trace sulfur containing gas mixture by functionalized UiO-66 (Zr) materials: a molecular simulation study. Fluid Phase Equilibria 427: 259–267.

**[55]** DeCoste, J.B., Demasky, T.J., Katz, M.J. et al. (2015). A UiO-66 analogue with uncoordinated carboxylic acids for the broad-spectrum removal of toxic chemicals. New Journal of Chemistry 39 (4): 2396–2399.

**[56]** Jawed, A., Saxena, V., & Pandey, L. M. (2020). Engineered nanomaterials and their surface functionalization for the removal of heavy metals: A review. Journal of Water Process Engineering, 33, 101009

**[57]** Muley, A.B., Mulchandani, K.H., and Singhal, R.S. (2020). Immobilization of enzymes on iron oxide magnetic nanoparticles: synthesis, characterization, kinetics and thermodynamics. In: Methods in Enzymology, Chapter 3, Nanoarmoring of Enzymes with Carbon Nanotubes and Magnetic Nanoparticles, vol. 630 (ed. C.V. Kumar), 39–79. Academic Press. https://www.sciencedirect .com/science/article/pii/S0076687919304185

**[58]** Binas, V., Venieri, D., Kotzias, D., and Kiriakidis, G. (2017). Modified TiO2 based photocatalysts for improved air and health quality. Journal of Materiomics 3 (1): 3–16.

**[59]** Petryshak, V., Mikityuk, Z., Vistak, M. et al. (2017). Highly sensitive active medium of primary converter SO2 sensors based on cholesteric-nematic mixtures, doped by carbon nanotubes. Przeglad Elektrotechniczny 1: 119–122

**[60]** Elsehly, E.M., Chechenin, N.G., Makunin, A.V. et al. (2018). Enhancement of CNT- based filters efficiency by ion beam irradiation. Radiation Physics and Chemistry 146: 19–25.

**[61]** Sharifi, M., Sohrabi, M.J., Hosseinali, S.H. et al. (2020). Enzyme immobilization onto the nanomaterials: application in enzyme stability and prodrug-activated cancer therapy. International Journal of Biological Macromolecules 143: 665–676.

**[62]** Yu, H., Liu, R., Wang, X. et al. (2012). Enhanced visible-light photocatalytic activity of Bi2WO6 nanoparticles by Ag2O cocatalyst. Applied Catalysis B: Environmental 111: 326–333.

**[63]** Huang, Y., Wang, W., Zhang, Y. et al. (2019). Synthesis and applications of nanomaterials with high photocatalytic activity on air purification. In: Novel Nanomaterials for Biomedical, Environmental and Energy Applications (ed. X. Wang and X. Chen), 299–325. Elsevier.

**[64]** Rodrigues-Silva, C., Miranda, S.M., Lopes, F.V.S. et al. (2017). Bacteria and fungi inactivation by photocatalysis under UVA irradiation: liquid and gas phase. Environmental Science and Pollution Research 24 (7): 6372–6381.

**[65]** Binas, V., Venieri, D., Kotzias, D., and Kiriakidis, G. (2017). Modified TiO2 based photocatalysts for improved air and health quality. Journal of Materiomics 3 (1): 3–16.

**[66]** Rezaee, A., Rangkooy, H., Khavanin, A., and Jafari, A.J. (2014). High photocatalytic decomposition of the air pollutant formaldehyde using nano-ZnO on bone char. Environmental Chemistry Letters 12 (2): 353–357.

**[67]** Vohra, A., Goswami, D.Y., Deshpande, D.A., and Block, S.S. (2006). Enhanced photocatalytic disinfection of indoor air. Applied Catalysis B: Environmental 64 (1, 2): 57–65.

**[68]** Guerra, F.D., Attia, M.F., Whitehead, D.C., and Alexis, F. (2018). Nanotechnology for environmental remediation: materials and applications. Molecules 23 (7): 1760.

**[69]** Mangematin, V., &amp; Walsh, S. (2012). The future of nanotechnologies. Technovation, 32(3-4), 157-160.

**[70]** Rao, C. N. R., &amp; Cheetham, A. K. (2001). Science and technology of nanomaterials: current status and future prospects. Journal of Materials Chemistry, 11(12), 2887-2894.

**[71]** Allarakhia, M., &amp; Walsh, S. (2011). Managing knowledge assets under conditions of radical change: The case of the pharmaceutical industry. Technovation, 31(2-3), 105- 117.

**[72]** Lee, Y. G., &amp; Song, Y. I. (2007). Selecting the key research areas in nano- technology field using technology cluster analysis: A case study based on National R&amp;D Programs in South Korea. Technovation, 27(1-2), 57-64.

**[73]** Loveridge, D., Dewick, P., &amp; Randles, S. (2008). Converging technologies at the nanoscale: The making of a new world. Technology Analysis &amp; Strategic Management, 20(1), 29-43.

**[74]** Walsh, S. T. (2004). Roadmapping a disruptive technology: A case study: The emerging microsystems and top-down nanosystems industry. Technological Forecasting and Social Change, 71(1-2), 161-185.

**[75]** Selin, C. (2007). Expectations and the Emergence of Nanotechnology. Science, Technology, &amp; Human Values, 32(2), 196-220.

**[76]** Youtie, J., &amp; Shapira, P. (2008). Mapping the nanotechnology enterprise: a multi- indicator analysis of emerging nanodistricts in the US South. The Journal of Technology Transfer, 33(2), 209-223.

**[77]** Gambardella, A., &amp; McGahan, A. M. (2010). Business-model innovation: General purpose technologies and their implications for industry structure. Long range planning, 43(2-3), 262-271

**[78]** Islam, N., &amp; Miyazaki, K. (2010). An empirical analysis of nanotechnology research domains. Technovation, 30(4), 229-237.

**[79]** Mauter, M. S., &amp; Elimelech, M. (2008). Environmental applications of carbon-based nanomaterials. Environmental science &amp; technology, 42(16), 5843-5859.

**[80]** Gopidas, K. R., Whitesell, J. K., &amp; Fox, M. A. (2003). Nanoparticle-cored dendrimers: synthesis and characterization. Journal of the American Chemical Society, 125(21), 6491-6502.

**[81]** Louie, S. M., Ma, R., &amp; Lowry, G. V. (2014). Transformations of nanomaterials in the environment. In Frontiers of Nanoscience (Vol. 7, pp. 55-87). Elsevier.

**[82]** Theron, J., Walker, J. A., &amp; Cloete, T. E. (2008). Nanotechnology and water treatment: applications and emerging opportunities. Critical reviews in microbiology, 34(1), 43-69.

**[83]** Xu, P., Zeng, G. M., Huang, D. L., Feng, C. L., Hu, S., Zhao, M. H., ... &amp; Liu, Z. F. (2012). Use of iron oxide nanomaterials in wastewater treatment: a review. Science of the Total Environment, 424, 1-10.

**[84]** Jain, K. K. (2008). Nanomedicine: application of nanobiotechnology in medical practice. Medical Principles and Practice, 17(2), 89-101.

**[85]** Kotov, N. A., &amp; Winter, J. O. (2009). Clements IP, Jan E. Timko BP, Campidelli S, Pathak S, Mazzatenta A, Lieber CM, Prato M, Bellamkonda RV. Nanomaterials for neural interfaces. Advanced Materials, 21(40), 3970-4004.

**[86]** Nezakati, T., Cousins, B. G., &amp; Seifalian, A. M. (2014). Toxicology of chemically modified graphene-based materials for medical application. Archives of Toxicology, 88(11), 1987-2012.

**[87]** Bhattacharyya, A., Datta, P. S., Chaudhuri, P., &amp; Barik, B. R. (2011, March). Nanotechnology-A new frontier for food security in socio economic development. In Disaster risk vulnerablity conference (pp. 116-120).

**[88]** Liu, R., &amp; Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the total environment, 514, 131-139.

**[89]** Liu, R., &amp; Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the total environment, 514, 131-139.

**[90]** Huang, P. J. J., &amp; Liu, J. (2013). Separation of short single-and double-stranded DNA based on their adsorption kinetics difference on graphene oxide. Nanomaterials, 3(2), 221-228.

**[91]** Ito, Y., &amp; Fukusaki, E. (2004). DNA as a ‘nanomaterial’. Journal of Molecular Catalysis B: Enzymatic, 28(4-6), 155-166.

**[92]** Lu, C. H., Willner, B., &amp; Willner, I. (2013). DNA nanotechnology: from sensing and DNA machines to drug-delivery systems. ACS nano, 7(10), 8320-8332

**[93]** Xu, L., Liu, Y., Chen, Z., Li, W., Liu, Y., Wang, L., ... &amp; Chen, C. (2012). Surface- engineered gold nanorods: promising DNA vaccine adjuvant for HIV-1 treatment. Nano letters, 12(4), 2003-2012.

**[94]** Dreizin, E. L. (2009). Metal-based reactive nanomaterials. Progress in energy and combustion science, 35(2), 141-167.

**[95]** Contado, C. (2015). Nanomaterials in consumer products: a challenging analytical problem. Frontiers in chemistry, 3, 48.

**[96]** Gajewicz, A., Rasulev, B., Dinadayalane, T. C., Urbaszek, P., Puzyn, T., Leszczynska, D., &amp; Leszczynski, J. (2012). Advancing risk assessment of engineered nanomaterials: application of computational approaches. Advanced drug delivery reviews, 64(15), 1663-1693.

**[97]** Zhang, Y., Liu, J. P., Chen, S. Y., Xie, X., Liaw, P. K., Dahmen, K. A., ... &amp; Wang, Y. L. (2017). Serration and noise behaviors in materials. Progress in Materials Science, 90, 358-460.

**[98]** Pumera, M. (2010). Graphene-based nanomaterials and their electrochemistry. Chemical Society Reviews, 39(11), 4146-4157.

**[99]** Tian, J., Xu, J., Zhu, F., Lu, T., Su, C., &amp; Ouyang, G. (2013). Application of nanomaterials in sample preparation. Journal of Chromatography A, 1300, 2-16.