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Challenges of Nanotechnology Applications in Addressing Environmental Pollution

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Abstract

Environmental application of nanomaterials to treat air, soil and wastewater pollutants has several advantages due to the unique properties of the nanoparticles. In the literature, there are many positive reports of effective treatment processes for different environmental pollutants based on nanotechnology. However, successful laboratory-scale experiments do not imply that there are no challenges and concerns for the environmental application of nanomaterials on a large scale. Here, in this review, we briefly discuss the sources and types of environmental pollutants, the problems associated with their existence, and the conventional and nanotechnological methods of addressing them. The challenges facing the environmental application of nanotechnology in the field of removing pollutants were also discussed, in addition to suggestions and recommendations to address these challenges.

Keywords: Nanotechnology; Environmental Pollutants; Nanomaterials; Challenges.

1. Introduction

Environmental pollution is a global problem that is inextricably linked with rapid industrialization and urbanization. It is the unfavorable alteration of our surroundings, wholly or largely as a byproduct of man's actions, through direct or indirect effects of the changes in the energy pattern, radiation levels, and chemical and physical constitution and abundance of organisms. In addition to the depletion of many natural resources, the modern lifestyle and the increasing population cause the production and accumulation of many pollutants in the environment. This accumulation of harmful pollutants represents a serious threat to the sustainability of the environment and human health as well [1,2]. Many scientific efforts, in the past and present, have been devoted to overcoming such environmental problems caused by pollution using conventional and modern technologies. Nanotechnology is a modern and rich field of research that could be directed in many areas of life including cleaning up the environment from hazardous wastes. However, the successes achieved through the application of nanotechnology to remove pollutants, these processes face many challenges and obstacles [3]. This review article, presents an overview for nanotechnology, its properties, its applications for pollutant removal in comparison with conventional removal methods. Moreover, an overall of challenges, hopes, and expectations for environmental nanotechnology applications are reviewed.

1. Environmental contamination

1.1. Sources and types of environmental contaminants

Different human activities results in many wastes that could be either in solid, liquid, or gaseous state. Moreover, the origin of these environmental pollutants may be organic or inorganic. For example, in agriculture sector, the use of pesticides results in air, soil and groundwater pollution in addition to the accumulation of pesticide residues in crops and agricultural products [4-6]. The excessive use of inorganic fertilizers causes most of these harmful

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agricultural chemicals to be discharged into drains and water bodies, and part of them also could accumulates in plants and crops [7]. Industry pollutants vary greatly according to the type of industry, the materials involved, the technical steps and precautions used during manufacturing. The textile dyes industry, for example, produced wastewater that contains many toxic waste dyes that pose a serious threat to the environment if discharged without proper treatment [8,9]. Mining and petrochemicals industries are known to release many contaminants to soil and aquatic environments [10]. In addition, cities and residential communities produce significant quantities of municipal solid wastes and municipal wastewater [11].

Regarding to contaminants nature, it could be biological (pathogenic bacteria, parasitic protozoa, or helminthes), inorganic (heavy metals) and organic contaminants. Some contamination sources contains many types of contaminants like domestic wastewater, which contains bacteria, parasitic protozoa, many nutrients (nitrogen and phosphorus) as well as heavy metals and toxic chemicals [12-14].

1.2. Problems associated with environmental contaminants

The degree of damage caused by pollutants varies according to their chemical composition, concentration, and degree of availability in the surrounding environment [15]. For instance, pesticides residues as toxic xenobiotics in soil and aquatic environments have adverse effect to the microflora, flora, and fauna. It has been reported that “as little as 1% of an applied pesticide reaches the target pest and the remainder ends up in soil, water, and air, ultimately entering our food chain and affecting non-target species including humans” [16]. Chlorinated hydrocarbons, and polychlorinated biphenyls (PCBs) are examples of toxic and stable compounds that commonly detected in low quality irrigation waters. The presence of these toxic chemicals in irrigation water is attributed to the excessive use of pesticides and the contamination of irrigation water with sewage. Reports indicates that the contamination with such toxic compounds is associated with negative impacts on both human’s and environmental health [17,18].

Heavy metals which are non-degradable inorganic metal elements with high molecular weight can accumulate in organs tissues and cause different toxicity levels [19]. Due to the inability of heavy metals to be metabolized in living organisms (of humans, terrestrial and aquatic animals and plants) it can bio-accumulates in their cells causing adverse effects. For instance, cadmium (which exhibits severe toxicity if present in drinking water even in low concentrations), can accumulate in human body for 10 - 33 year as accumulation half–life. Accumulated heavy metals can interfere with body's functions causing many neurological and mental symptoms and failing functions of many organs such as the kidneys and liver [20,21].

Dye wastewater from textile industry represent a threat to the environment due to the inherent toxicity of the synthetic (organic and inorganic) chemicals that used as dyes. Unfortunately, in many cases such toxic dyes pollutants discharged into water bodies without appropriate remediation treatment [22]. Reactive azo dye for instance, is “widely used in textile, paper, pharmaceutical, cosmetic, and food industries” [23]. Its toxicity is based on benzidine and its congeners, dimethyl- and dimethoxybenzidine that reported to cause humans bladder cancer and “hepatocellular carcinomas and hepatic neoplastic nodules in rats” [24].

Wastewaters from different sources (e.g. agricultural waste runoff, and industrial sewage) can degrade water quality and trigger eutrophication in lakes. This eutrophication “not only adversely impacts local ecosystems, but also poses potential risks to public health” [25]. Irrigation of crops with untreated or partially treated wastewater results in its contamination with different pathogens and toxic heavy metals, hence affect human’s health. In addition to the harmful effect of toxic substances in wastewater on aquatic organisms, the fertility and chemical and physical properties of the soil are also negatively affected [17,18].

1.3. Conventional methods for environmental contaminants removal

Over time, wastes and pollutants accumulated in the environment surrounding humans, who tried to get rid of this problem by various available methods. For centuries, people have been burning or burying the solid wastes in their surroundings to prevent their accumulation. Recently, composting has been widely applied as a bioremediation strategy for solid organic wastes [26]. For heavy metal removal from wastewater treatment, many conventional methods have been established, developed and applied for decayed. Such methods includes “chemical precipitation, photocatalysis, ion exchange, membrane filtration, and adsorption of inorganic materials, chemical oxidation, reduction, reverse osmosis, electrodialysis” [27,28]. Wastewater (municipal and industrial) that contains high organic load commonly subjected to “preliminary treatment, primary treatment, secondary treatment, tertiary treatment, disinfection, and solids handling” processes [29,30]. Recently, there has been an increase in reliance on the use of different bioremediation techniques to get rid of organic and inorganic pollutants using bacteria, yeasts, fungi, microalgae, and plants or their enzymes. Bioremediation, compared to physical and chemical alternatives, has a number of advantages such as ecofriendly and sustainability [31]. However, many limitations still face the full success of applying biological treatment to eliminate environmental pollutants. Therefore, the trend has been made to use and exploit nanotechnology approaches to eliminate lifestyle-threatening organic and inorganic pollutants in many different environments.

2. Applications of Nanotechnology

Nanotechnology is relatively modern field of applied science that concern with design, synthesis, characterization and application of nanomaterials and devices**.** Nanotechnology generally involves the application of materials and structures with one or more nanoscale dimensions (i.e. 1 -100 nanometers) [9,32]. It covers a wide range of applications based on the unique properties of developed nano-scale materials. Such nanomaterials used to develop new products, enhancement of present products, and enhancing the performance of different chemical and biochemical reactions [33,34]. Depending on its dimensions, there are many forms of engineered nanomaterials such as nanoparticle, nanorode, nanotube, nanofiber, nanodendrimers, nanoplate and nanoribbon [35]. On the other hand, the nanomaterials can be classified based on matter phases to nanocomposite, nanofoam, nanoporous materials and nanocrystalline materials (**Fig. 1**) [36]. Whereas, based on their nature or origin, the nano-scale materials may be classified into natural or artificial. In addition, the field of application (medicine, pharmaceutical, environment, computer science, space, agriculture, food industry, etc.) plays a crucial factor in nanomaterials classification [37].

Nanotechnology intersects with the sciences of biology, physics and chemistry enabling a massive field of applications (**Fig. 2**). Some of these application areas can be summarized as following:

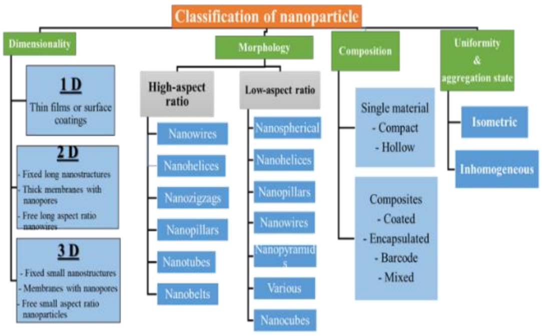

Fig. 1. Classification of nanoparticle based on deferent ways

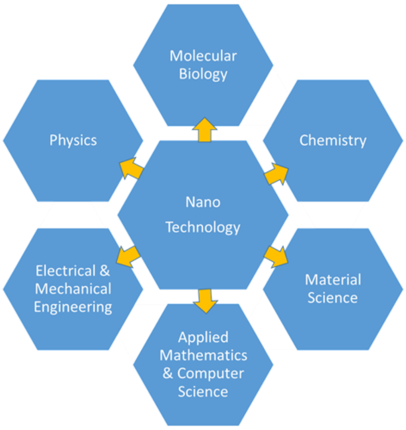

Fig. 2. Relation between nanotechnology and other fields of science

2.1. Environmental applications

Nanotechnology is being used successfully to enhance the efficiency of many important environmental applications such as municipal / industrial wastewater treatment, water desalination and purification. Moreover, the unique properties of nanomaterials are of critical importance in increasing the efficiency of biological treatment processes for soil and land and purifying polluted air. In addition, many materials gain increased antimicrobial properties when present in nano-form and thus can be used efficiently in disinfecting pathogens in soil, water and air [38-40].

2.2. Nano agriculture applications

Many agricultural applications have benefited from technologies based on nanomaterials to improve their efficiency and reduce their costs. For example, the use of nanomaterials for fertilization (nanofertilizers), control of plant pathogens (nanopesticides), production of nanosensors and many equipments to increase and improve agricultural production [41-43].

2.3. Food industry

Nanotechnology has contributed to a paradigm shift in the entire food industry by making changes in the way food is produced, processed, packaged and transported. The application of nanotechnology to these processes must go hand in hand with ensuring the safety and security of the nanomaterials used as well as the resulting food products. Since the introduction of nanotechnology in the field of food processing is relatively recent, a good nutritional cultural awareness must be created to improve the consumer acceptance of such products [44-46].

2.4. Nanotextile applications

Nanotextile is defined as "any textile made by using the tools of nanotechnology". The application of nanomaterials in textile industry includes manufacturing of fibers (nano-fibers), finishing of fabrics, and manufacturing of textile dyes. The application of nanomaterials in the textile industry allows improving the properties of fibers and imparting some additional distinctive properties to the produced fabrics. For example, some nanostructures possess the ability to give the produced fabric an antimicrobial property (medical clothing) or to change its color according to surrounding temperature [47,48]. However, despite the many advantages of nanotextile applications, there is a possibility of environmental contamination with nanomaterials during manufacturing of fabrics after disposing consumed clothes. Antimicrobial clothes that contain silver nitrate nanoparticles are of most suspected source of contamination with silver nanoparticles either during manufacturing or after disposing clothes.

2.5. Medical and pharmaceutical applications

Many medical applications have been benefits from the unique properties of nanoparticles. Some of those applications include cancer treatment, *in vivo* imaging, sensing, blood purification, tissue engineering, medical devices. Regarding pharmaceutical applications, there are many applications for nanomaterials. For instance, nanosized materials could be used to improve formulation and delivery of drugs. In addition, new drug materials could be synthesized based on nanotechnology for medical application [49,50].

3. Application of nanotechnology for wastewater treatment

Human activities generate huge quantities of wastewater (domestic, industrial, and agricultural) which, if not treated adequately, lead to serious environmental and health problems. In pursuit of effective treatment methods for polluted water, scientists have tended to take advantage of the unique properties of nanomaterials in treating industrial and wastewater. Some of these efforts are summarized below:

3.1. Nanosorption and Nanoadsorption

As a result of the massive increase in the surface area of nanomaterials, the absorbent materials in nanoscale allow a high ability to absorb pollutants. Sometimes the high absorption capacity of nanomaterials can be specific to certain pollutants. Several recently developed hybrid sorbents such as nanopolymer compound have been shown to have successful applications in removing contaminants. These adsorbed pollutants can be organic and inorganic materials such as heavy metals, dyes and hydrocarbons in various types of wastewater. Nanopolymers provide adjustable properties, improved handling capability, high stability, and a large surface area for rapid decontamination. In addition, some of these nano-adsorbents have a high selectivity to remove various pollutants, with high efficiency, thus reduce the cost of wastewater treatment [51,52].

3.2. Nanodendrimers for wastewater treatment

Nanodendrimers are nano-sized, radially symmetric molecules with well-defined, homogeneous and monodisperse structure that has a typically symmetric core, an inner and outer shell. Deferent dendrimers has biological properties as self-assembling, polyvalency, electrostatic interactions, low cytotoxicity, solubility and chemical stability. Upon the previous characteristics, dendrimers are good choice in the field of wastewater treatment [53]. In order to wastewater treatment, dendrimers could be applied for enhancing and developing this technology for removing a lot of pollutant at the same time based on some mechanisms like anion-binding, cation-binding, organic compound-binding, viral-binding, biological compound-binding and them combinations. Ultra-filtration membranes (UFM) need less energy than reverse osmosis or nano-filtration, but it isn't effective in eradicating dissolved inorganic and organic solutes due to their small size.

The connection of dendrimers with UFM could allow the efficient removal technology for radionuclide, toxic metal ions, bacteria, organic and inorganic solutes and viruses [54].

3.3. Nanofilteration and Nanomembrane

Nanofiltration (NF) is a fairly recent membrane filtration procedure (Fig. 3) used to reduce total insoluble solids in wastewater and remove disinfection precursors used with low total dissolved solids in wastewater (such as natural and synthetic organic matter) and remove microbial load. Membrane technology is an efficient filtration technique due to its reliable pollutant removal without production of any dangerous by-products. Membrane filtration depends on the pressure of wastewater through semi-permeable membranes that allow the passage of liquids, gases and dissolved particles while preventing insoluble particles [55,56].

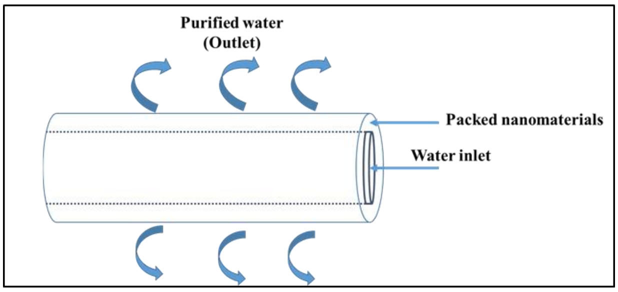

Fig. 3. Nanofilter design for wastewater treatment

3.4. Immobilization of biodegrading enzymes

Magnetic nanoparticles (Fe_3O_4) are applied for immobilization of enzymes that responsible for biodegradation of pollutants as peroxidase enzymes. This immobilization of enzymes on magnetic nanoparticles usually enhanced their efficiency and stability properties. Moreover, this immobilization enables the multi reusability of degrading enzymes for many bioremediation cycles. The result enzyme is stable toward different environmental and storage conditions (**Fig. 4**) [57]. The immobilized enzymes on magnetic nanoparticles can be potentially applied in several industrial and environmental applications.

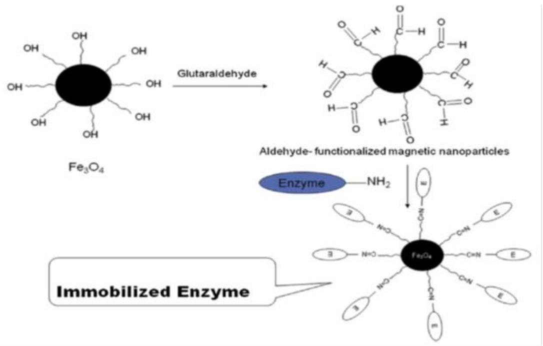

Fig. 4. Schematic diagram for immobilization of enzyme using magnetic nanoparticles

3.5. Nanofibers for wastewater treatment

Nanofiber technology is considered the advanced method in industrial wastewater treatment process in combination with biological removal of toxic xenobiotics. The formation of biofilm can be significantly maintained applying structures in nanofiber form and the system becomes stable and faster biodegradable. Nanofibers can be applied in the nonwoven structures form, support layer, stand-alone membranes or surface modification layer to increase the composite material functionality. Continuous research has been done for optimizing the design and structure of nanofiber membrane by process, operating material and surrounding parameters in the process of electrospinning [58].

3.6. Nanodisinfection for wastewater treatment

Antimicrobial activity of several nano-sized metal ions lets for design of nanocatalysts such as AgNPs, CuO, TiO_2 and ZnO [38]. The high efficacy of nanoparticles led to remove microbial pathogens from wastewater. The crucial role of nanomaterials during wastewater treatment communicates on their antimicrobial activity during disinfection, control of membrane biofouling and biofilm formation control on different surfaces [59]. There are several ways of applying the nanomaterials in water disinfection processes [60]:

a. Preventing the passage of electrons through the bacterial membrane.
b. Breakdown the cell membrane.
c. Oxidation of cellular components such as protein.
d. Hydroxyl radicals.
e. Damage of cellular components such as DNA.

As mentioned in the previous section, nanotechnology has many positive applications related to wastewater treatment, also, it has a lot of negative effects. Thus, we can point these impacts as follows:

4. Challenges of environmental nanotechnology applications

Despite the numerous promising environmental applications based on nanotechnology that have proven successful on a laboratory scale, there are many challenges faces a real application on a large scale.. Such challenges can be classified into technical, economic, health, social, and environmental challenges.

4.1. Technical challenges

There are some technical limiting factors that consist a challenge for the application of nanotechnology for pollutants removal. Some of these challenges are the “loss of reactivity with time, transportation, and their effect on beneficial microorganisms” [61]**.** In addition, many of the prefigured solutions are still in the stage of "proof-of-concept" or only at pilot trials. Also, there is a dearth of risk assessment studies that are supposed to be conducted to estimate the harmful potentials due to the use of nanomaterials. Such studies should be conducted in conjunction with the development of the production and use of nanotechnology in various fields, especially the environment. However, limited knowledge concerning nanomaterial fate, adverse effects, biosafety and developed biological reactivity once dispersed into the environment, requires further scientific efforts to measure potential nano-environmental risks [62,63].

General technical challenges for nanotechnology applications as general could be summarized as following:

1. The methods for nanoparticle analysis in environment; the new nanomaterials are regularly daily developed by different size and shape (important factors in toxicity determining).
2. Information about the chemical structure is a serious issue to measure the material toxicity and the slight changes of active group could extremely change its properties.
3. Evaluation of full risk assessment (exposure risk and its probability) for the human health safety and environmental impact at all nanotechnology stages such as toxicological analysis, persistence risk, transport and transform risk and ability to recycle.
4. Assessment of life cycle risk.
5. Good experimental design in advance of engineering nanomaterials.
6. Requiring high energy for some nanomaterials synthesizing.
7. Distribution of toxic persistent nano-substances into environmental pollution.
8. Lower rates of recycling and recovery.
9. Environmental associations with other life cycle stages aren't clear.
10. Absence of qualified workers and engineers.
11. Absence of adequate database for structure, applications, and environmental fate of nanostructured materials.

4.2. Economic challenges

Financial cost is often a major challenge facing many new applications. Nanotechnology applications are among those that face significant challenges from an economic point of view. In this regard, it should be noted that the cost of synthesizing and quantifying nanocomposites is relatively large. This high cost is a hindrance to many researchers. Also, when starting to actually implement some nanomaterial-based technologies on a large scale, the economic cost is overestimated for many countries [64,65].

4.3. Health challenges

Risks of human health related to nanotechnology contain nanoparticles exposure at the workplace or inhalation via contaminated air, water or food ingestion and dermal contact, mainly through the application of private care products. The effects of nanoparticles on human include oxidative stress, genotoxicity, lipid peroxidation, lung diseases, pulmonary pathological changes, inflammation *etc*. [33]. Furthermore, DNA mutations and damage to mitochondria resulting in a cell death also noted. These worries over safety may boundary the common applications of NMs for remediation of environment.

4.4. Social challenges

In some situations, people's lack of knowledge of the importance of nanotechnology is an obstacle to its application in many fields. Hence, people's acceptance of the application of nanotechnology requires a lot of effort and awareness of its importance [60].

4.5. Ecological challenges

In contrast to laboratory experiments, the widespread application of nanoparticles to environmental applications has many risks and unintended consequences. For example, the release of some toxic nanomaterials such as silver nanoparticles into terrestrial or aqueous environments poses a serious environmental problem. The composition of microbial community also could be affected due to the presence of certain nanoparticles. Moreover, the fate of the nanocomposites must be monitored in different environments to determine whether or not they have lost part of their function. In addition, the dose–response effect and the exposure pathways how NMs enter an organism should be considered. A previous research has exposed the nanoparticles have adverse effects on microbial pure cultures as *Bacillus subtilis*, *Pseudomonas fluorescens*, *E. coli* and *Aspergillus niger* [66,67].

The potential concerns and challenges of applying nanoparticles in addressing environmental pollutants include several points such as:

4.5.1. Nanoparticle Transformations

Transformations of individual nanoparticles vary in the environment based on their origin, composition, and amount, in addition to their pathway or release into the environment. Transformations encompass a large number of chemical and physical processes including aggregation or agglomeration, dissolution, redox reactions, and exchange of surface cracks or interactions with biomolecules (**Fig. 5**). These transformations, in turn, affect the fate, transport, and toxicity of the nanoparticles in the environment, are making them crucial to understanding and characterizing these transformations [68].

4.5.2. Nanopollution and Nanowaste

Nanopollution is a general name for all wastes caused by nanodevices or through the process of nanomaterials engineering. Nanowaste is mostly the particles group that released into the environment, or the particles that are thrown away when still on their products. Ecotoxicological impacts of nanoparticles and the potential for bioaccumulation in plants and microorganisms is a subject of current research, as nanoparticles are considered to present novel environmental impacts [69]**.** Nanowaste can be the residue of industrial or commercial processes. Due to the broad range of existing nanomaterials, a single procedure for disposal will not suffice for all classes of nanomaterials. Hence, it is important to understand the properties of specific nanowastes before developing effective disposal practices. The developed safety measures and disposal procedures necessary for handling nanowaste must be based on current knowledge and take into account existing legislation. The disposal procedures must ensure that the waste is deactivated of its hazardous properties. Depending on the type of the material, thermal, chemical or physical processing of nanotechnology-containing waste is possible deactivation solutions [70].

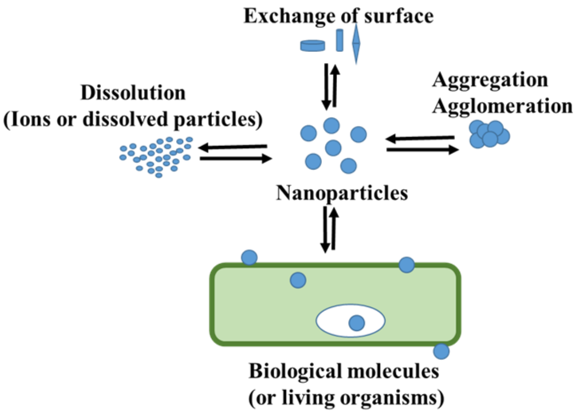

Fig. 5. Nanoparticles transformations in environmental sectors

4.5.3. Ecotoxicity of nanomaterials

Most studies published on toxicity have concentrated on considerate the NM potential risks in mammalian organisms, with incomplete examinations by other biological systems as plants, fungi, invertebrates, amphibians, reptiles or bacteria. Consequently, our considerate on the NMs risk effects and nano-products are incomplete.

4.5.4. Toxicity evaluation methods

A lot of studies proposed that the NPs could be easily entered into human body due to their nanoscale dimension is similar size to typical cellular components [71]. The challenge of assessing and classifying methods for nanowastes sufficiently is carefully associated with the methods adopted in founding the NM toxicity. It is suggested that studies on hazard assessment should consider actual nanowaste watercourses. These studies should be planned to income into account all the related biotic and abiotic factors in order to offer the most accurate threat of the nanowastes. The best data should be resulted to explain the potential carrier ability of NMs to other environmental pollutants, whether the detected toxicity is due to separate NMs or aggregated form and how actual environmental factors impacts nanowastes risk.

4.5.5. Nanomaterials properties

The size and shape of nanosize materials is considered the main factor for nanotechnology applications. The nanometer size of the materials makes it difficult for monitoring and tracking in the environment. Additionally, initial studies correlated to nanoparticles chemical reactivity and toxicity show thoughtful worries that require new, ideal removal and recovering trials. Hundreds of millions dollars are paid every year on nanotechnology relating research, but much less money or concern is settled for developing tools for facilitating use and removing of nanowastes. International Organization for Standardization (ISO) developed a sequence of standards in 2010 [72,73], which illustrate vocabulary for nanotechnology applications. To the current time, there are no standards that tell exactly to the safe removal or nanomaterials recycling. This is mainly due to the large diversity of nanomaterials that applied and the varying methods required for each. The size of waste containing deposit nanoparticles is increased daily with its application in municipal wastewater [74].

5. Conclusion

The pollutants remediation based on nanotechnology is a relatively new field of applied science. Despite the successful application at the laboratory level in removing pollutants using nanotechnology, there is a need for careful steps towards environmental applications on a large scale due to the presence of many technical, economic, health and environmental challenges. Technical /

economic and risk assessment studies should be taken into account to assess the overall perspectives and potentials for the use of nanomaterials in general and in the environmental sector in particular.

6. Conflicts of Interest

The authors declare no conflict of interest.

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