Different Applications of Nanomaterials and Their Impact on the Environment

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Abstract
Today nanotechnology has become a top research field in the world. The present review covers classification and different applications of nanomaterials including catalysis, water treatment, sensors, energy storage and nanomedicine, as well as their positive and negative impacts on the environment. Increased attention needs to be directed towards the new nanomaterials because the development of knowledge of these nanoparticles is still in its infancy. Nanoparticles are ultra-small particles with exceptional properties, but some nanoparticles and nanomaterials also exhibit harmful properties. This is the reason why we must continue to study them and their potentially damaging effects.

Keywords - *nanoparticles, nanomaterials, environment, nanomedicine, catalysis.*

I. INTRODUCTION

Nanotechnology is an interdisciplinary study which allows us to develop new materials with new, interesting and useful properties. These new materials are nanomaterials made from nanoparticles. Nanoparticles are ultra-small particles with exceptional properties which can direct medicines straight to the place where the human body needs them, they can make materials stronger and they can convert solar energy more efficiently. Nanoparticles possess different properties and behave differently to the classical, larger building blocks of substances. From a scientific point of view, these interesting new properties are not so much the results from the fact that nanoparticles are small, but they result from the fact that a particle consisting of a relatively limited number of molecules behaves and interacts differently with its surroundings for fundamental physical reasons. Nanoparticles and nanomaterials have gained prominence in technological advancements due to their adjustable physicochemical characteristics such as melting point, wettability, electrical and thermal conductivity, catalytic activity, light absorption and scattering resulting in enhanced performance over their bulk counterparts. By controlling the shape, size and internal order of the nanostructures, properties (electrical conductivity, colour, chemical reactivity, elasticity, etc.) can be modified [1, 2].
Recently, China has made significant advances and currently has the fastest growing nanotechnology publications and related industrialization. China is still left behind by American nanotechnology in terms of average citations per papers and publications in high impact journals, efforts appear less organized in the European Union [3].

II. NANOPARTICLES AND NANOMATERIALS

According to the European Commission, a nanomaterial is defined as a “natural, incidental, or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm” [4].
Consequently, with a wide range of applications available, these particles have potential to make a significant impact to the society. Although new, the history of nanomaterials dates long back to 1959, when Richard P. Feynman, a physicist at Cal Tech, forecasted the advent of nanomaterials. In one of his classes he said, “There is plenty of room at the bottom,” and suggested that scaling down to nano-level and starting from the bottom was the key to future technology and advancement [5].

Generally, based on the construction, nanomaterials are currently classified as (i) carbon-based, (ii) metal-based, (iii) dendrimers, and (iv) composites [6].
Generally, carbon-based NMs contain carbon, and are found in morphologies such as hollow tubes, ellipsoids or spheres.

Metal-based NMs are metal based materials that we commonly regarded as quantum dots, nanogold, nanosilver and oxides with metal bases. Titanium dioxide is one such example. They are a focus of the biomedical and pharmaceutical industries. Dendrimers are branched components that form polymers and whose surface exhibit chain ends are suited for chemical manipulation as tools. Dendrimers are combinable to create hollow cavities or used as part of a catalysis. Dendrimers represent a half step between molecular chemistry and polymer chemistry [7]. The application of dendrimers is through biomedicine with applications as anticancer drugs, pain management, and timed released medications such as a transdermal patch or in gene therapy.

Composites are combination of nanoparticles or nanoparticles and other materials. Nanoparticles, such as nanosized clays, are already being added to products ranging from auto parts to packaging materials, to enhance mechanical, thermal, barrier, and flame-retardant properties [8].

Although Ag, zinc oxide (ZnO), copper oxide (CuO), cerium dioxide (CeO_2), titanium dioxide (TiO_2), iron oxide (FeO), fullerenes, carbon nanotubes (CNTs), and a small number of others remain the most widely used and researched nanomaterials (NMs), some newer NMs have been produced in recent years. The greatest interest and development has been in broad classes of materials including nanocomposites and nanohybrids. Nanocomposites are NMs enclosed or encapsulated with other materials, which may not have nanoscale features, whereas nanohybrids are the linking of 2 or more discrete NMs to give different functionality [9]. Such NMs can be based on semiconductor substrates such as GaAs, CdSe, CdS, SiGe, and others, modified with shells and coatings, along with mixtures of carbon–carbon and carbon–metal or metal oxides [10]. The evolution of nanotechnology today in the area of the food industry has been largely and has had a lot of contribution in the food processing, food package, and food preservation [11]. Bratovcic and co-workers pointed out the achievements of nanotechnology using polymer nanocomposites and nano additives in the field of food packaging [12].

Figure 1 shows classification and wide range of applications of nanomaterials.

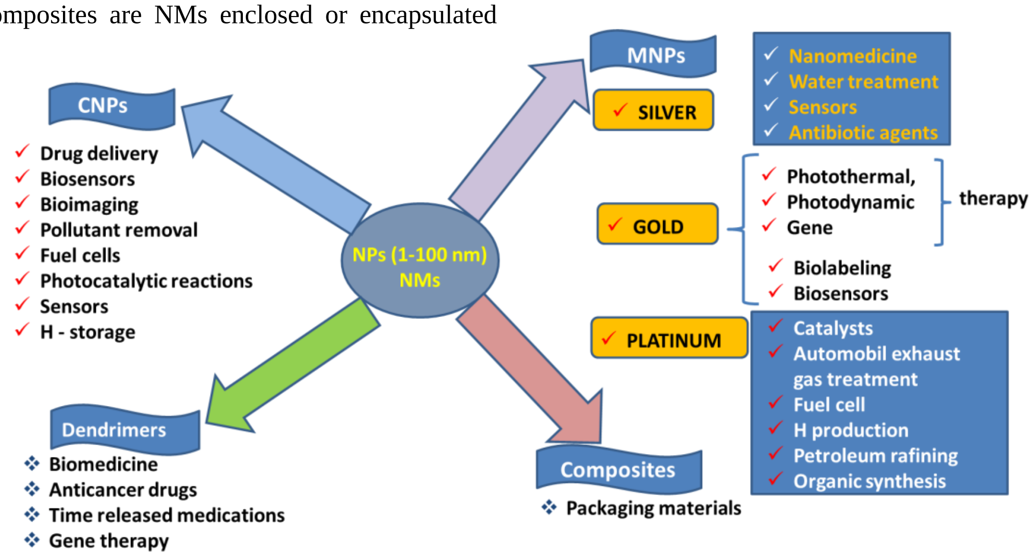

Fig 1: Classification and wide range of applications of nanomaterials

We will more focus here on carbon and metal based nanomaterials and their applications.

A. Application of Nanomaterials

Specifically, gold, silver, zinc etc. nanomaterials possess unique physicochemical properties which gain a great deal of attention in biomedical applications, while platinum in energy storage.

There is growing interest in utilizing the optical properties of silver nanoparticles as the functional component in various products and sensors. Silver nanoparticles are extraordinarily efficient at absorbing and scattering light and, unlike many dyes and pigments, have a colour that depends on the size and the shape of the particle. It has become increasingly popular as antibiotic agents in textiles and wound dressings, medical devices, and appliances such as refrigerators and washing machines [13].

Carbon-based NMs are widely used in numerous fields such as drug delivery, enzyme immobilization, biosensors, bioimaging and pollutant removal [14].

1) Catalysis

Catalysis is one of the pioneer applications of nanoparticles. Various elements and materials like aluminium, iron, titanium dioxide, clays, and silica all have been used as catalysts in nanoscale for many years. In recent years, nanocatalysis has become an emerging field of science due to its high activity, selectivity and productivity. The small metal nanoparticles in a range of 1–10 nm exhibit extraordinary catalytic activity, sometimes better than the corresponding metal complexes. The high activity of nanocatalysts is attributed to several important factors, including the high surface-to-volume ratio, surface geometric effect, the electronic effect, as well as the quantum size effect. Metal nanoparticles suspended in solution are often used as effective heterogeneous catalysts due to the advantages of simplified isolation of product and facile recovery and excellent recyclability, which renders metal nanocatalysts environmentally friendly. The catalytic performance (e.g., conversion and selectivity) of nanocatalysts is drastically influenced by the size of metal nanoparticles [15]. By using catalytic reagents, one can reduce the temperature of a transformation, reduce reagent-based waste and enhance the selectivity of a reaction that potentially avoids the unwanted side reactions leading to a green technology. In the absence of catalyst, variety of products i.e. medicines, fine chemicals, polymers, fibres, fuels, paints, lubricants, and a countless of other value added products essential to humans, would not be feasible [16]. Thus, by using catalysts, manufacturing protocols can be made more economic, green and sustainable. In the field of chemistry, carbon nanotubes can be used as catalysts for partial oxidation of fuel cells, synthetic ammonia and methane, and widely used in photocatalytic reactions.

2) Water treatment

The application of nanomaterials in water and wastewater treatment has drawn wide attention. Due to their small sizes and thus large specific surface areas, nanomaterials have strong adsorption capacities and reactivity. Heavy metals [17], organic pollutants [18], inorganic anions [19], and bacteria [20] have been reported to be successfully removed by various kinds of nanomaterials [21]. In recent years, photocatalytic degradation by metal oxide nanoparticles such as TiO_2 has been successfully applied in the contaminant degradation in water and wastewater. TiO_2 has been a highly researched material because of its non-toxicity, chemical stability, commercial availability, high photoactivity, etc. [22; 23; 24]. At the presence of light and catalyst, contaminants can be gradually oxidized into low molecular weight intermediate products and eventually transformed into CO_2, H_2O, and anions such as NO_3^-, PO_4^{3-} and Cl^- [25].

3) Sensors

The development of a wide array of nanomaterials has paved the way for their applicability in the design of high-performance electrochemical sensing devices for medical diagnostics and environment and food safety. The review of [26] has shown that different nanomaterials for the electrochemical determination of some common additives and contaminants, including hydrazine (N_2H_4), malachite green (MG), bisphenol A (BPA), ascorbic acid (AA), caffeine, caffeic acid (CA), sulfite (SO_3^{2-}) and nitrite (NO_2^-), which are widely found in food and beverages have been synthetized.

Nanotechnology has profoundly influenced the area of biosensors, particularly through their high sensitivity and selectivity, as well as the miniaturization of sensor devices. In this context, fluorescent nanomaterials and nanostructures have been used in order to develop new nanostructured biosensors for glucose sensing. The electrochemical method for sensing glucose is widely used among diabetes patients in the form of a blood glucose meter [27]. Carbon nanotubes can also be used for the development of molecular detection, such as gas sensors, small molecular sensors, electrochemical detectors and chromatographic applications. Modification of the macroelectrode with nanoparticles and other nanomaterials reduces the detection limit and improves the degree of sensitivity and selectivity of measurements [28].

4) Energy storage

Platinum-based nanomaterials have attracted much interest for their promising potentials in the fields of energy-related and environmental catalysis. Platinum (Pt), possesses rich electronic structure and exhibits excellent catalytic activities in a series of catalytic processes, including automobile exhaust gas treatment, fuel cell, petroleum refining, organic synthesis, and hydrogen production [29]. The Pt-based NMs significantly increase specific surface area and number of exposed active sites, thus, the utilization of Pt atoms greatly increase [30; 31;32]. Researchers at Rice University are using carbon nanotube films to stop the growth of dendrites on lithium metal anodes. This step may help develop lithium metal batteries, which could have a much higher capacity and faster charging than lithium ion batteries. Lithium metal charges much faster and holds about 10 times more energy by volume than the lithium-ion electrodes found in just about every electronic device, including cellphones and electric cars. They coated a lithium metal foil with a multiwalled carbon nanotube film. Researchers at Rice University have developed electrodes made from carbon nanotubes grown on graphene with a very high surface area and very low electrical resistance. The researchers first grow graphene on a copper substrate then grow carbon nanotubes on the graphene sheet. Because the base of each nanotube is bonded, atom to atom, to the graphene sheet the nanotube-graphene structure is essentially one molecule with a huge surface area.

5) Nanomedicine

The properties of silver nanoparticles such as broad-acting and potent antibacterial activity are widely investigated. A wide range of nanosilver applications has emerged in consumer products ranging from disinfecting medical devices and home appliances to water treatments, as well as in nanomedicine.

Research interest in biocompatible gold nanoparticles has been highly increased in recent years for potential applications in nanomedicine due to their fascinating size dependent chemical, electronic and optical properties. Some of its relevant applications like photothermal therapy, drug delivery, photodynamic therapy, gene therapy, biolabeling, biosensing, etc., are revolutionizing the field of biomedicine that attracts enormous research attention [33]. AuNPs are non-cytotoxic in nature with an additional advantage of a huge surface area, which makes their surfaces accessible for modification with targeting molecules, which make them advantageous over other nanoparticles for various biomedical applications. Targeted drug delivery is the most efficient therapy since it is possible to target only the affected cells or part. This minimizes the side effects of drugs. This is useful in treating cancer where the medicines can be delivered directly to the affected cells without damaging healthier cells in any way. Quantum dots [34] Fe_3O_4 [35]; [36] and ZnO [37] are effectively used for targeted drug delivery. Gold nanoparticles can be used for the bio-imaging of biosensing and labelling. Gold nanoparticles have been used as contrast agents in cellular or molecular imaging for a long time [38]. A novel sensor for the colorimetric detection of Salmonella typhimurium based colour change effect of gold nanoparticles was developed by Ma and co-workers [39]. Gold nanoparticles are extensively used in biosensing applications these days [40; 41]. Determination of blood glucose level [42], detection of bacteria [43], viruses, detection of pollutants [44] and monitoring pathogens [45] can be effectively carried out by biosensing.

III.IMPACT OF NANOMATERIALS ON THE ENVIRONMENT

The growing production and use of NMs in diverse industrial processes, construction, and medical and consumer products is resulting in increasing exposure of humans and the environment. Humans encounter nanomaterials from many sources and exposure routes, including ingestion of food, direct dermal contact through consumer products and by inhalation of airborne nanomaterials [46]. The increasing use of nanomaterials in our life or the customer productions has inevitably caused the accumulation exposure of the nanoparticles into the environment, yet the fate of these particles may greatly depend on their environmental mediums, physical or chemical property. Therefore, the superficial area of nanoparticles and other physicochemical properties may greatly influence their transformation and bioavailability during spreading into environment. However, there are still no fully comprehensive systems to establish the assessments for potential effects of pollution between toxicity and nanoparticles in the environment.

The structures are affecting the environment by a number of routes, e.g., 1) by increasing the pollution level of air, water, and soil, 2) by accumulating in the environmental system (short term and long term effects), and 3) by affecting the life-cycle of living systems present in environment.

As lacking of quantitative analytical methods to trace those related nanoparticles, additionally, the concentrations of the nanoparticles be exposed in environmental mediums are still ambiguous. The analysis of nanomaterials in environmental samples often requires the use of multiple technologies in tandem. Characterization methods include spectroscopy, microscopy, chromatography, centrifugation, filtration and others [47]. One of the main methods of analysing single nanomaterial characteristics is electron microscopy. Scanning electron microscopy and transmission electron microscopy can be used to determine the size, shape and aggregation state of nanomaterials below 10 nm. Nanoparticles may enter the aquatic environment instantly via industrial release, dumping of wastewater treatment effluents, and/or through surface runoff from soils [48].

A. *Positive Impacts on the Environment*

Engineered nanomaterials exhausted into the atmospheric environment tend to be exposed to sunlight and UV wavelengths at significantly higher degrees than those released into other compartments [49]. This exposure is likely to increase the possible outcomes of photochemical changes to nanomaterials. Positive and negative impacts on the environment are presented in figure 2.

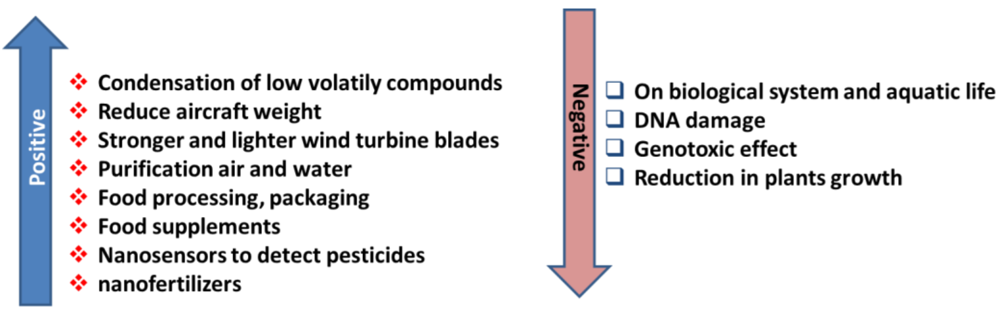

Figure 2. Positive and Negative Impact on the Environment

Nanomaterials are used in aircrafts as a substitute of conventional composites to help reduce aircraft weight, saving thousands of tons of fuel [50]. Furthermore, nanomaterials are applied in wind turbine blades to make them stronger and lighter, helping increase their energy conversion efficiency [51]. Nanomaterials are progressively used in automotive exhaust systems and petroleum refining systems to boost chemical reactions while reducing pollution and expenses [52]. Nanomaterials have been successfully implemented for the purification of air and water by means of adsorption, filtration, and oxidation techniques with greater efficiency than conventional techniques. Nanosilver particles have a broad antibacterial effect on a range of Gram-negative and Gram-positive bacteria and antibiotic-resistant bacteria strains [53].

Nanosilver is an effective antifungal agent against a broad spectrum of common fungi. NSPs can inhibit the growth of *Candida albicans*, *Candida glabrata*, *Candida parapsilosis*, *Candida krusei*, and *Trichophytonmentagrophytes* effectively.

In recent years, the use of nanotechnology in food safety has gained increasing attention. Nanotechnology based detection systems vary in their mechanisms and designs but they share the same goal, that is, timely and accurate detection of trace pathogens or other contaminants [54]. Nanotechnology is of great use in many fields, in particular in the agrofood industry, where is it used primarily in: primary production, food processing and packaging and food supplements [55]. Nanotechnology has many applications in varied fields from nanosensors to monitor the livestock health (pigs, sheep), [56; 57; 58] to control soil cultivation conditions [59; 60] and to detect pesticides in crops [61]. Nanotechnology applications have the potential to change agricultural production by allowing better management and conservation of inputs of plant and animal production. Nanofertilizers have beneficial effects over conventional ones. This is the case of the use of zinc oxide nanoparticles in Zn fertilizers to increase their solubility [62; 63]. De la Rosa et al. [64] found that by applying zinc oxide nanoparticles through the foliar spray, growth and biomass of alfalfa, tomato, and cucumber can be increased.

Claudia Francely Cumplido-Nájera and co-workers showed that the application of copper nanoparticles and potassium silicate changed the levels of enzymatic and non-enzymatic compounds that are key in defence of tomato plants, increasing the tolerance to *C. michiganensis*. Also, the loss of yield due to the bacteria was reduced by 16.1% [65].

B. Negative impacts on the environment

New nanomaterials may react with biomolecules, cells, organs and organisms in a new and unexpected way. Therefore exposure of humans and the environment to nanomaterials may result with possible negative impacts [66]. Public and regulatory acceptances are additional elements in nanotechnology that have been required. This is primarily focused on the health and safety of the materials and products including the environmental impact. Some materials are wonderful at a particular task but are not acceptable due to their environmental impact [67]. Toxicological function is affected by the particle size, compounds, or aggregation of these nanoparticles. Currently, some literatures have pointed negative influence upon the aquatic organisms with the emergence of nanoparticles in aqueous condition or at aqueous interface [68].

There are some negative effects of nanomaterials on biological systems and the environment caused by nanoparticles, like chemical hazards on edible plants after treatment with high concentration of nanosilver, also, in some cases, nanomaterial generated free radicals in living tissue leading to DNA damage, therefore nanotechnology should be carefully evaluated before increasing the use of the nanoagromaterials [69].

Recently, scientists have investigated the ecological effects of Ag_2S nanoparticles. As the uptake of nanoparticles led to the upregulation of genes, reduction in the plants growth was accompanied. As the majority of the Ag_2S nanoparticles were accumulated at the leaves of the tested plants, such phenomenon increased the chances of trophic transfer of these structures through food chain. The transfer of certain nanoparticles such as TiO_2 was also seen to cause genotoxic effect (at low dose of 0.25 mM) to damage DNA (at higher concentrations) on the plants, e.g., *Allium cepa* and *Nicotiana tabacum* [70].

The presence of NMs was also demonstrated to exert low to high toxicity impacts on aquatic life. According to the toxicological investigations, nanomaterials may affect unicellular aquatic organisms and creatures (e.g., fish and Daphnia) [71]. Several studies suggest that the toxicity of silver nanoparticles is attributed to their release of silver ions in cells as both silver nanoparticles and silver ions have been reported to have similar cytotoxicity [72]. Although the details of the toxic mechanism are unclear, it suggests that nanosilver particles are ionized in the cells, which leads to activate ion channels and changes the permeability of the cell membrane to both potassium and sodium, interaction with mitochondria, and induction of the apoptosis pathway via the production of reactive oxygen species, which leads to cell death [73].

IV. CONCLUSION

From this review, it is concluded that despite the advancement and development of new nanomaterials, they still have positive and negative effects both on the environment and on human beings. Accordingly, nanomaterials can be compared as drugs because it is well known that they have both desired and undesirable effects. Until now, nanomaterials have been explored for many different applications in diverse sectors including catalysis, sensing, photovoltaic, energy, environment, and biomedical. However, the level of nanomaterials in the environment is consistently increasing. The hazards of nanomaterials to plants, animals and microbes has had an indirect effect on our humans. Increased attention needs to be directed towards the new nanomaterials because the development of knowledge of these nanoparticles is still in its infancy. Since the shape, size and composition of nanoparticles can have both significant effects on their function and possible risks to human health, extensive research is needed to fully understand their synthesis, characterization, and possible toxicity.

REFERENCES

[1] Martín-Gago, J.A., Casero, E., Briones, C., Serena, P.A., 2009. Nanociencia y Nanotecnología. Entre la ciencia ficción del presente y la tecnología del futuro. Fundación Española para la Ciencia y la Tecnología FECYT, Madrid.

[2] Serena, P., 2016. Guía específica de trabajo sobre "nanotecnología para la revolución urbana: ciudades inteligentes".

[3] Haiyan Dong, YuGao, PatrickJ.Sinko, ZaishengWu, Jianguo Xu, Lee Jia, The nanotechnology race between China and the United States, Nano Today 11, (2016), 7—12.

[4] European Commission, 2016. Recommendation on the Definition of a Nanomaterial. http://data.europa.eu/eli/reco/2011/696/oj.

[5] Appenzeller T., The man who dared to think small, Science. 1991 Nov 29;254(5036):1300.

[6] Saleh, T.A., 2016. Nanomaterials for pharmaceuticals determination. Bioenergetics 5, 226. https://doi.org/10.4172/2167-7662.1000226.

[7] Elham Abbasi, Sedigheh Fekri Aval, Abolfazl Akbarzadeh, Morteza Milani, Hamid Tayefi, Nasrabadi, Sang Woo Joo, Younes Hanifehpour, Kazem Nejati-Koshki, and Roghiyeh Pashaei-Asl, Dendrimers: synthesis, applications, and properties, Nanoscale Res Lett. 2014, 9(1): 247.

[8] Classification of Nanomaterials, The Four Main Types of Intentionally Produced Nanomaterials, 2007, https://www.azonano.com/article.aspx?ArticleID=1872 on date 03.01.2019.

[9] Saleh NB, Aich N, Plazas-Tuttle J, Lead JR, Lowry GV. 2015. Research strategy to determine when novel nanohybrids pose unique environmental risks. Environ Sci Nano 2:11–18.

[10] Wu W, Jiang C, Roy VAL. 2015. Recent progress in magnetic iron oxide–semiconductor composite nanomaterials as promising photocatalysts. Nanoscale 7:38–58.

[11] Alshammari Fanar Hamad, Jong-Hun Han, Byung-Chun Kim, Irfan A. Rather, The intertwine of nanotechnology with the food industry, Saudi Journal of Biological Sciences 25 (2018) 27–30.

[12] A. Bratovčić, A. Odobašić, S. Ćatić, I. Šestan, Application of polymer nanocomposite materials in food packaging, Croat. J. Food Sci. Technol. (2015) 7 (2) 86-94.

[13] Rineesh NR, Neelakandan MS, Thomas S (2018) Applications of Silver Nanoparticles for Medicinal Purpose. JSM Nanotechnol Nanomed 6(1): 1063.

[14] Chen, M., Qin, X., Zeng, G., Biodegradation of carbon nanotubes, graphene and their derivatives, Trends Biotechnol. 35, (2017), 836-846.

[15] Gao Li, Rongchao Jin, Catalysis by gold nanoparticles: carbon-carbon coupling reactions, Nanotechnol Rev 2013; 2(5): 529–545.

[16] Santosh Bahadur Singh, Praveen Kumar Tandon, Catalysis: A Brief Review on Nano-Catalyst, Journal of Energy and Chemical Engineering, 2014, 2, 3, pg.106-115.

[17] W.-W. Tang, G.-M. Zeng, J.-L. Gong et al., "Impact of humic/fulvic acid on the removal of heavy metals fromaqueous solutions using nanomaterials: a review," Science of the Total Environment, vol. 468-469, pp. 1014–1027, 2014.

[18] Yan J., L. Han,W. Gao, S. Xue, andM.Chen, "Biochar supported nanoscale zerovalent iron composite used as persulfate activator for removing trichloroethylene," Bioresource Technology, vol. 175, pp. 269–274, 2015.

[19] Liu F., Yang J. H., Zuo J. et al., "Graphene-supported nanoscale zero-valent iron: removal of phosphorus from aqueous solution and mechanistic study," Journal of Environmental Sciences, vol. 26, no. 8, pp. 1751–1762, 2014.

[20] Kalhapure R. S., Sonawane S. J., Sikwal D. R. et al., "Solid lipid nanoparticles of clotrimazole silver complex: an efficient nano antibacterial against Staphylococcus aureus and MRSA, Colloids and Surfaces B: Biointerfaces, vol. 136, pp. 651–658, 2015.

[21] Haijiao Lu, Jingkang Wang, Marco Stoller, Ting Wang, Ying Bao, Hongxun Hao, An Overview of Nanomaterials for Water and Wastewater Treatment, Advances in Materials Science and Engineering, Volume 2016, Article ID 4964828, http://dx.doi.org/10.1155/2016/4964828

[22] Zhao, Z.M.; Sun, J.; Xing, S.M.; Liu, D.J.; Zhang, G.J.; Bai, L.J.; Jiang, B.L. Enhanced Raman scattering and photocatalytic activity of TiO_2 films with embedded Ag nanoparticles deposited by magnetron sputtering. J. Alloys Compd. 2016, 679, 88–93.

[23] Guo, Q.; Zhou, C.Y.; Ma, Z.B.; Ren, Z.F.; Fan, H.J.; Yang, X.M. Elementary photocatalytic chemistry on TiO_2 surfaces. Chem. Soc. Rev. 2016, 45, 3701–3730.

[24] Zheng, L.X.; Han, S.C.; Liu, H.; Yu, P.P.; Fang, X.S. Hierarchical MoS_2 nanosheet@TiO_2 nanotube array composites with enhanced photocatalytic and photocurrent performances. Small 2016, 12, 1527–1536.

[25] A. Bratovcic, Photocatalytic degradation of organic compounds in wastewaters, Technologica acta, ISSN 1840-0426, accepted review paper, 2019.

[26] Venkatesh S. Manikandan, BalRam Adhikari, Aicheng Chen, Nanomaterial based electrochemical sensors for the safety and quality control of food and beverages, Analyst, 19, 2018

[27] Longyi Chen, Eugene Hwang, Jin Zhang, Fluorescent Nanobiosensors for Sensing Glucose, Sensors 2018, 18(5), 1440; doi:10.3390/s18051440

[28] Brainina Kh., Stozhko N., Bukharinova M., Vikulova E., Nanomaterials: Electrochemical Properties and Application in Sensors, Physical Sciences Reviews, Vol. 3, 9, 2018, doi: https://doi.org/10.1515/psr-2018-8050

[29] Sibin Duan, Zhe Du, Hongsheng Fan, Rongming Wang, Nanostructure Optimization of Platinum-Based Nanomaterials for Catalytic Applications, nanomaterials, 2018, 8, 949; doi:10.3390/nano8110949

[30] Wolf, O.; Dasog, M.; Yang, Z.; Balberg, I.; Veinot, J.G.; Millo, O. Doping and quantum confinement effects in single Si nanocrystals observed by scanning tunneling spectroscopy. Nano Lett. 2013, 13, 2516–2521.

[31] Sichert, J.A.; Tong, Y.; Mutz, N.; Vollmer, M.; Fischer, S.; Milowska, K.Z.; Garcia Cortadella, R.; Nickel, B.; Cardenas-Daw, C.; Stolarczyk, J.K.; et al. Quantum size effect in organometal halide perovskite nanoplatelets. Nano Lett. 2015, 15, 6521–6527.

[32] Wu, J.; Yang, H. Platinum-based oxygen reduction electrocatalysts. Acc. Chem. Res. 2013, 46, 1848–1857.

[33] Murali K, Neelakandan MS, Thomas S (2018) Biomedical Applications of Gold Nanoparticles. JSM Nanotechnol Nanomed 6(1): 1064.

[34] Qi L, Gao X. Emerging application of quantum dots for drug delivery and therapy. Expert Opin Drug Deliv. 2008; 5: 263-267.

[35] Chertok B, Moffat BA, David AE, Yu F, Bergemann C, Ross BD, et al. Iron oxide nanoparticles as a drug delivery vehicle for MRI monitored magnetic targeting of brain tumors. Biomaterials. 2008; 29: 487-496.

[36] Chen FH, Gao Q, Ni JZ. The grafting and release behavior of doxorubicin from Fe_3O_4@ SiO_2 core-shell structure nanoparticles via an acid cleaving amide bond: the potential for magnetic targeting drug delivery. Nanotechnol. 2008; 19: 16.

[37] Rasmussen JW, Martinez E, Louka P, Wingett DG. Zinc oxide nanoparticles for selective destruction of tumor cells and potential for drug delivery applications. Expert Opin Drug Deliv. 2010; 7: 1063- 1077.

[38] Hutter E, Maysinger D. Gold nanoparticles and quantum dots for bioimaging. Microsc Res Tech. 2011; 74: 592-604.

[39] Ma X, Song L, Zhou N, Xia Y, Wang Z, A novel aptasensor for the colorimetric detection of S. Typhimurium based on gold nanoparticles, Int. J. Food Microbiol., 2017, doi: 10.1016/j.ijfoodmicro.2016.12.024

[40] Dykman L, Khlebtsov N. Gold nanoparticles in biomedical applications: recent advances and perspectives. Chem Soc Rev. 2012; 41: 2256- 2282.

[41] Saha K, Agasti SS, Kim C, Li X, Rotello VM. Gold nanoparticles in chemical and biological sensing. Chem Rev. 2012; 112: 2739-2779.

[42] Bhumkar DR, Joshi HM, Sastry M, Pokharkar VB. Chitosan reduced gold nanoparticles as novel carriers for transmucosal delivery of insulin. Pharm Res. 2007; 24: 1415-1426.

[43] Phillips RL, Miranda OR, You CC, Rotello VM, Bunz UH. Rapid and Efficient Identification of Bacteria Using Gold-Nanoparticle–Poly (para-phenyleneethynylene) Constructs. Angew Chem Int Ed Engl. 2008; 47: 2590-2594.

[44] Alvarez-Puebla RA, dos Santos DS Jr, Aroca RF. SERS detection of environmental pollutants in humic acid-gold nanoparticle composite materials. Analyst. 2007; 132: 1210-1214.

[45] Li F, Zhao Q, Wang C, Lu X, Li XF, Le XC. Detection of Escherichia coli O157: H7 using gold nanoparticle labeling and inductively coupled plasma mass spectrometry. Anal Chem. 2010; 82: 3399-3403.

[46] Laux, P., Riebeling, C., Booth, A.M., Brain, J.D., Brunner, J., Cerrilo, C., Creutzenberg, O., Estrela-Lopis, I., Gebel, T., Johanson, G., Jungnickel, H., Kock, H., Tentschert, J., Tlili, A., Schaffer, A., Sips, A., Yokel, R.A., and A. Luch. 2017. "Biokinetics of nanomaterials: The role of biopersistence." NanoImpact. Volume 6. Pg 69 – 80.

[47] Gmiza, K., Patricia Kouassi, A., Kaur Brar, S., Mercier, G., and J. Blais. 2015. Quantification and Analyses of Nanoparticles in Natural Environments with Different Approaches. Nanomaterials in the Environment. Pg 159 -177

[48] Batley, G.E., Kirby, J.K., McLaughlin, M.J., 2013. Fate and risks of nanomaterials in aquatic and terrestrial environments. Acc. Chem. Res. 46 (3), 854–862. https://doi.org/10.1021/ar2003368.

[49] Mitrano, D.M., Motellier, S., Clavaguera, S., Nowack, B., 2015. Review of nanomaterial aging and transformations through the life cycle of nano-enhanced products. Environ. Int. 77, 132–147.

[50] Kausar, A., Rafique, I., Muhammad, B., 2017. Aerospace application of polymer nanocomposite with carbon nanotube, graphite, graphene oxide, and nanoclay. Polym. Plast. Technol. Eng. 56 (13), 1–19.

[51] Patel, V., Mahajan, Y.R., 2017. Techno-commercial Opportunities of Nanotechnology in Wind Energy. Wiley VCH Verlag GmbH & Co. KGaAhttps://doi.org/10.1002/9783527696109.

[52] Etim, U., Peng, B., Yan, Z., 2018. Nanotechnology Applications in Petroleum Refining. pp. 37–65. https://doi.org/10.1007/978-3-319-60630-9_2.

[53] Durán N, Marcato PD, Alves OL, Souza GIH, De, Esposito E. Mechanistic aspects of biosynthesis of silver nanoparticles by several Fusarium oxysporum strains. J Nanobiotechnology. 2005; 3: 8.

[54] Banerjee, T., Shelby, T., Santra, S., 2017. How can nanosensors detect bacterial contamination before it ever reaches the dinner table? Future Microbiol. (2), 12.

[55] Elena Villena de Francisco, Rosa M. García-Estepa, Nanotechnology in the agrofood industry, Journal of Food Engineering 238 (2018) 1–11.

[56] Patil, S.S., Kore, K.B., Kumar, P., 2009. Nanotechnology and its applications in veterinary and animal science. Vet. World 2 (12), 475–477.

[57] Chalco, W.R., 2011. Nanotecnología en la Industria Alimentaria (Tesis de Master). Universidad Politécnica de Madrid, Madrid.

[58] Manuja, A., Kumar, B., Singh, R.K., 2012. Nanotechnology developments: opportunities for animal health and production. Nanotechnol. Dev. 2 (1), 17–25.

[59] Plasencia, C., 2008. Avances de la Nanotecnología en el Sector Agroalimentario. II Jornada AIN. "Aplicaciones Industriales de la Nanotecnología", Barcelona.

[60] Gogos, A., Knauer, K., Bucheli, T.D., 2012. Nanomaterials in plant protection and fertilization: current state, foreseen applications, and research priorities. J. Agric. Food Chem. 60 (39), 9781–9792.

[61] Pradhan, N., Singh, S., Ojha, N., Shrivastava, A., Barla, A., Rai, V., Bose, S., 2015. Facets of nanotechnology as seen in food processing, packaging and preservation industry. BioMed Res. Int. 2015 365672.

[62] Milani, N., McLaughlin, M.J., Stacey, S.P., Kirby, J.K., Hettiarachchi, G.M., Beak, D.G., Coprnelis, G., 2012. Dissolution kinetics of macronutrient fertilizers coated with manufactured zinc oxide nanoparticles. J. Agric. Food Chem. 60 (16), 3991–3998.

[63] Milani, N., Hettiarachchi, G.M., Kirby, J.K., Beak, D.G., Stacey, S.P., McLaughlin, M.J., 2015. Fate of zinc oxide nanoparticles coated onto macronutrient fertilizers in an alkaline calcareous soil. PLoS One 10 (5), e0126275.

[64] De la Rosa, G., López-Moreno, M.L., de Haro, D., Botez, C.E., Peralta-Videa, J.R., Gardea-Torresdey, J., 2013. Effects of ZnO nanoparticles in alfalfa, tomato, and cucumber at the germination stage: root development and X-ray absorption spectroscopy studies. Pure Appl. Chem. 85 (12), 2161–2174.

[65] Claudia Francely Cumplido-Nájera, Susana González-Morales, Hortensia Ortega-Ortíz, Gregorio Cadenas-Pliego, Adalberto Benavides-Mendoza, Antonio Juárez-Maldonado, The application of copper nanoparticles and potassium silicate stimulate the tolerance to Clavibacter michiganensis in tomato plants, Scientia Horticulturae 245 (2019) 82–89.

[66] E.A.J. Bleeker, S. Evertz, R.E. Geertsma, W.J.G.M. Peijnenburg, J. Westra, S.W.P. Wijnhoven, Assessing health and environmental risks of nanoparticles current state of affairs in policy, science and areas of application, RIVM Report 2014-0157.

[67] Mike Pitkethly, Nanotechnology, regulation and the environment, materialstoday, 12, (2009), 1-2, pg 23.

[68] Duoxi Yao, Zheng Chen, Kui Zhao, Qing Yang, Wenying Zhang, Limitation and challenge faced to the researches on environmental risk of nanotechnology, Procedia Environmental Sciences 18, (2013), 149 – 156.

[69] Susan Dekkers, Agnes G. Oomen, Eric A.J. Bleeker, Rob J. Vandebriel, Christian Micheletti, Joan Cabellos, Gemma Janer, Natalia Fuentes, SocorroVázquez-Campos, Teresa Borges, Maria JoãoSilva, Adriele Prina-Mello, DaniaMovia, Fabrice Nesslany, Ana R.Ribeiro, Paulo Emílio Leite, Monique Groenewold, Flemming R. Cassee, Susan W.P. Wijnhoven, Towards a nanospecific approach for risk assessment, Regulatory Toxicology and Pharmacology, 80, 2016, 46-59.

[70] Ghosh, M., Bandyopadhyay, M., Mukherjee, A., 2010. Genotoxicity of titanium dioxide (TiO_2) nanoparticles at two trophic levels: plant and human lymphocytes. Chemosphere 81, 1253–1262.

[71] Gao, M.L., Zhang, Z., Lv, M.T., Song, W.H., Lv, Y.H., 2018. Toxic effects of nanomaterial adsorbed cadmium on Daphnia magna. Ecotoxicol. Environ. Saf. 148, 261–268.

[72] Abou El-Nour KMM, Eftaiha A, Al-Warthan A, Ammar RAA. Synthesis and applications of silver nanoparticles. Arab J Chem. 2010; 3: 135- 140.

[73] Ravindran A, Chandran P, Khan SS. Biofunctionalized silver nanoparticles: Advances and prospects. Colloids Surf B Biointerfaces. 2013; 105: 342-352.