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REVIEW ARTICLE

Development of Nanomaterials as Photo Catalysts for Environmental Applications

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Abstract: Lack of environmental sustainability is a growing and pivotal matter due to the issues such as disturbances associated with biodiversity pollution and climate change. Pollutants are the major cause of these environmental threats in the atmosphere. At present, nano-based photocatalysts are at the forefront of the author's interest because of their promising potential as a green chemical-based compound, high catalytic activity, suitable and controllable surface area for wastewater treatment. Semiconductor materials on a nano-sized scale have electronic and optical properties depending on their building block size, which plays a vital role in developing smart materials that are well-efficient for simultaneously destroying harmful chemical contaminants from our environment. This makes these materials useful in many possible industrial applications, such as water purification. In this review, we have reported the most significant results contributing to the progress in the area of environmental hazardous pollutant detection and removal focused on water purification especially through photocatalysis to give readers an overview of the present research trends. Moreover, we have analyzed previous studies to indicate key principles of photocatalysis and provide guidelines that can be used to fabricate more efficient photocatalysts.

Keywords: Photocatalysis, semiconductors, nanomaterials, water purification, pollutants, green chemistry.

1. INTRODUCTION

Clean water production technology has received much research interest owing to water insufficiency, resource depletion, and global warming. This interest was reflected in a number of published research studies on photocatalysis for wastewater treatment in recent years. According to the web of science database search, the number of published studies on photocatalysis for wastewater treatment in 2009 was 3.232; whereas, in 2019, the number of publications increased by almost 800% to reach 24.262 studies. In particular, many researchers were interested in studying the various properties of the corresponding photocatalysis nanostructures, such as nanoparticles, nanofiber, nanorods, nanowires, nanoneedles, and nanotubes, etc., which are much more attractive than bulk counterpart due to their promising applications in wastewater treatment. A recent Educational, Scientific and Cultural Organization (UNESCO) report revealed that every day, many people die due to diseases caused by water pollution, and the lack of availability of quality drinking water, especially in the developing nations. These statistical figures are likely to grow soon, as water contamination is increasing due to the continuous discharge of micropollutants and contaminants into the natural water cycle. The cleanup of these contaminants may also be very costly and complex. Recently, photocatalytic oxidation processes have been successfully utilized for the elimination of contaminants from wastewater. This was one of the most important reasons why scientists were interested in developing this promising technology for water purification.

2. NANOTECHNOLOGY FOR WASTEWATER TREATMENT

Nanotechnology, at present, plays a vital role in water treatment approaches. Nanotechnology is defined as the science and technology dealing with the material at the nanoscale. In nanotechnology, nano nanostructures are used to soften the water and remove the physical, biological, and chemical contaminants. Due to the exceptional physicochemical properties which resulted from size quantum confinement and the dominance of interfacial phenomena, such as tunable photoactivity, adsorption properties, high reactivity, and many other interesting characteristics, nanostructured

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materials represent one of the most active research topics and development worldwide in recent years [1-12]. Many authors have reported that nanomaterials can be used as effective catalysts for removing various pollutants in water and, thus, have been successfully applied in wastewater treatment. Consequently, researchers have begun to work on developing innovative approaches to produce new materials, to replace existing production equipment, and to reproduce novel materials and chemicals with improved performance resulting in less consumption of energy and materials and reduce harm to the environment. Rapid use of pesticides, herbicides, dyes, solvents, etc. in agriculture and industrial development activities is causing a lot of problems and concern for scientific societies and environmental regulatory authorities around the world. These organic pollutants adversely influence the environment and it is considered a primary source of aesthetic pollution, nutrition, and ecological disturbance in aquatic life because of their toxicity and continuity. The application of nanotechnology in the cleanup of contaminated water could be summarized as:

- Nanoscale filtration techniques (Nanofiltration using membranes),
- Nanoadsorbents (sorbents, nanoclays, zeolites),
- Nanocatalysis (nano-sized semiconductor catalyst for environmental cleanup),
- Nanocomposites (Mixture of two or more nanoparticles to enhance the efficiency)

Various techniques, such as nano- photocatalysis, nanofiltration, adsorption, and electrochemical oxidation, may be used in the water treatment process. Many materials formed in the nanoscale, such as Titanium dioxide (TiO_2), Zinc Oxide (ZnO), polymer membranes, ceramic membranes, carbon nanotubes, nanowire membranes, submicron nanopowder, metal (oxides), magnetic nanoparticles, are used to solve or significantly reduce water quality problems in the natural environment [13,14].

Nanostructures, such as nanoparticles, nanomembrane, nanosheets, nanoflowers, and nanowires, etc., used for the detection and removal of chemical and biological contaminants include heavy metals, nutrients, pesticides, cyanide, organics, algae, viruses, bacteria, parasites, and antibiotics [14]. The detoxification and recycling of wastewater is a process that combines heterogeneous catalysis with solar-catalytic treatment [15]. Historically, photocatalysis was first mentioned in the year 1911 in a research report where ZnO was used as a photocatalyst to degrade dyes [16,17]. Heterogeneous photocatalytic systems utilize solid phase photoactive semiconductors like TiO_2, SnO_2, ZnO, etc., as photocatalysts for the degradation of various contaminants in wastewater [18].

For the treatment of chemical contaminants in wastewater effluents, various methods such as chemical oxidation, biological methods, combustion, flocculation, adsorption on carbon (granular activated), air stripping, and precipitation have been employed so far. These methods have limitations such as high cost and ineffectiveness. The biggest drawback is the degrading of the organic chemicals completely, converting them into secondary contaminants [19]. Photocatalysis has emerged as a green technology for the complete mineralization of hazardous organic to water, carbon dioxide, and simple mineral acids, and occurs at room temperature. Photocatalysis is a light-induced reaction which is enhanced by the presence of a catalyst [20].

3. GREEN CHEMISTRY APPROACH VIA PHOTOCATALYSIS

The use of solar energy is an interesting aspect of science. Solar photocatalysis has, thus, become a very important field in wastewater treatment research, where sunlight is the lighting source for performing various catalytic reactions. The application of the photocatalytic water purification process has gained great attention due to its efficiency in the decomposition and mineralization of the rebel organic compounds as well as the possibility of using the solar spectrum, UV rays, and visible light [21].

The important point of this process is that it can degrade or detoxify various organic chemicals, which have not been degraded in other ways of purification [22]. One of the major applications of photocatalysis has been in solar water splitting and the purification of air, which is considered as one of the so-called advanced oxidation processes. In photocatalysis, the catalyst is fully regenerated after the reaction. A good photocatalyst should absorb light efficiently and preferably in the visible or near-ultraviolet portion of the electromagnetic spectrum [23]. Adequate electron states (i.e. holes) must be sufficient to prevent re-pairs of electronic holes when exposed to light. Photocatalysts of nanostructures provide large surface-to-volume ratios, allowing for higher absorption of target particles or contaminants on the surface as well as a large reaction on the surface [24].

The prospect of employing semiconductor nanocrystals in photocatalysis offers several unique benefits related to spatially-extended charge separation and visible-range light absorption, which have been confirmed through a compelling performance in reduction half-reactions. For such systems to become practical, however, additional challenges need to be resolved. These pertain to the semiconductor photo corrosion, short excited-state lifetimes, and poor control over energy transfer to catalytic sites. To resolve these issues, several emerging strategies have been proposed and discussed. Among potential solutions, harnessing nanocrystals as triplet sensitizers of photoredox coordination compounds is expected to enhance the absorption characteristics of the latter while decreasing the damage of the semiconductor. Assemblies of inorganic colloids can also be used for funneling the photoinduced energy to reactive sites in a manner analog to the action of chlorophylls in PSII. This geometry could inspire a cascade-like design of photosynthetic assemblies for water oxidation [25].

Heterogeneous photocatalysis is currently a promising technique for water purification compared to other conventional techniques, whereby complex long-chain organic molecules (i.e. toxic) can be broken down into simpler parts as well as deform cell walls of microbes and thus, immobilize them [26, 27]. Heterogeneous photocatalysis is a process in which there are two active solid and liquid phases. The solid phase is a catalyst, usually, a semiconductor, based on catalyst irradiation, and another semiconductor, which may be photoexcited to form electron donor sites (reduction sites) and electronic receiving sites (oxidation sites), providing a large range as oxidation and reduction reactors [28]. Photocatalysis completely degrades the pollutant and complete mineralization is also achieved in case of pesticides and other toxicants [29]. The object of destructive oxidation processes is to mineralize organic contaminants, *i.e.*, convert them to carbon dioxide and water and other harmless products. Photocatalytic degradation is used to treat waste streams that are very dilute to burn and very concentrated for biological treatment and contain highly toxic organic compounds [30, 31].

Table **1** shows the various pollutants degraded by using photocatalyst nanoparticles of metal oxides as effective photocatalysts.

Table 1. Examples of different semiconductors employed for the degradation of pollutants using Photocatalysis.

Contaminant	Nano-photocatalyst	References
Dyes	-	-
Methyl orange	UV/TiO_2 on glass ZnO/ZnS N-TiO_2 SnO_2 CNTs/P-TiO_2 SnS_2 Fe^{3+}-TiO_2-Zeolite Fe_3O_4/ZnO	[33, 34]
Methylene Blue	LiFe/$(WO_4)_2$ SiOC/ZnO TiO_2/SiO_2 ZnO/Au BSA/CdS Co/ZnO Zn-Al-In(MMO) ZnO/TiO_2 Eu_2O_3-ZnO Gd_2O_3–CdO	[9, 33, 35 -38]
Congo Red	TiO_2/SiO_2 TiO_2/Sulfanilic acid Chitosan/CdS SnO_2	[24, 25,34, 39, 40]
Rhodamine B	$BiFeO_3$ Ag-TiO_2 P-TiO_2 ZnO/CuO TiO_2/ZrO_2 CeO_2-ZnO UV/TiO_2 bilayer $MgFe_2O_4$/TiO_2 Ag_3PO_4 Bi_xSb_2-xS_3	[24, 28, 41-45]
Heavy metals	-	-
Cr(VI)	magnetic 3D-TiO_2@Hierarchical Porous Graphene Aerogels (HPGA) nanocomposite:	[46]

Table 1. Contd…

Contaminant	Nano-photocatalyst	References
Pd(II) , Cd(II) , Cu(II) , Zn(II)	Rhodium/antimony co-doped TiO_2 nanorod and titanate nanotube (RS-TONR/TNT) composite	[47]
Phenol Bisphenol A	Ag/TiO_2 CdS/TiO_2 TiO_2-$ZnFe_2O_4$ WOx/TiO_2 Fe-TiO_2	[14, 32, 46]
Pesticides/Herbicides	-	-
Glyphosate	Ce-TiO_2	[30]
Sulfonylurea	$TiO_2/ZnO/SiO_2$	[24, 26, 27]
Organophosphate & Phosphonoglycine	UV/TiO_2 immobilized on silica gel	[29, 42]
Dichlorvos organophosphorus	WO_3. GO-doped nano-TiO_2	[48]
Organic Pollutant	$InVO_4$ TiO_2 Ag/ZnO TiO_2/Ni Ag/ Ag_2SO_3 MFe_2O_4 (M = Co, Ni, Cu, Zn)	[30, 49- 52]
Contaminated soil	Plasma/TiO_2 ((Degussa P25) nitrogen-doped TiO_2	[50, 53- 55]

The important observation here is that the more exposed the surface area, the more adsorption of the target molecules. Thus, the efficiency of the catalyst for degrading the target will increase. The biggest challenge of the use of nanoparticles for practical applications is the difficulty of removing the particles after-treatment process. To solve this problem, an additional process step is required for the post-separation of the catalysts. This separation process is crucial to avoid the loss of catalyst particles and the introduction of the new pollutant of contamination of TiO_2 in the treated water [32].

The catalyst recovery can be achieved through hybridization with conventional sedimentation, cross-flow filtration, or various membrane filtrations. Research is going on in the field of particle entrapment over the membrane to prevent the loss of the catalyst [33].

4. MECHANISM OF THE SEMICONDUCTOR AS PHOTOCATALYSTS

Photocatalysis, based on semiconductors, has been reported as a promising approach to destroy toxic and hazardous organic compounds in industrial wastewater and drinking water. Systematic studies of photocatalytic reactions are of prime importance both for a major understanding of the nature of heterogeneous photocatalysis and for optimizing its efficiency [56]. Photocatalytic degradation of organic substances is based on semiconductor photochemistry [57]. When a semiconductor materials building blocks are irradiated by the light of energy higher or equal to its bandgap, the electron from the valance band is excited to the conduction band with simultaneous generation of a hole (h^+) in the valence band, VB and electron (el^-) in the conduction band, CB [58]. According to band theory, each solid can be distinguished by two active energy ranges: valence band, VB, which has less energy, fully filled with electrons; and conduction band, CB, with higher energy, empty at 0° K. The interest ranges in photocatalysis are manned valence band and largely vacant conduction, which is usually characterized by energy gap (E_g) [59-62]. When the semiconductor is illuminated with a higher energy light (hυ) than the bandgap energy, the electron is promoted from VB to CB leaving a positive hole in the valence band and an electron in the conduction band. The holes facilitate the oxidation of organic compounds by forming hydroxyl radicals, and the electrons mediate the reduction and oxidation reactions by forming the superoxide radicals [63, 64].

The mechanism of the photocatalytic degradation can be explained with the following reaction steps taking TiO_2 as a model catalyst:

1. Absorption of efficient photons ($h\nu \geq E$G=3.2 eV) by Titanium dioxide:

$$(TiO_2)+ h\nu \rightarrow e^{-CB} + h^{+\,VB} \quad (1)$$

2. Oxygen ion sorption (first step of oxygen reduction;

oxygen's oxidation degree passes from 0 to −1/2):

$$(O_2)ads+ e^{-CB} \rightarrow O_2 \quad (2)$$

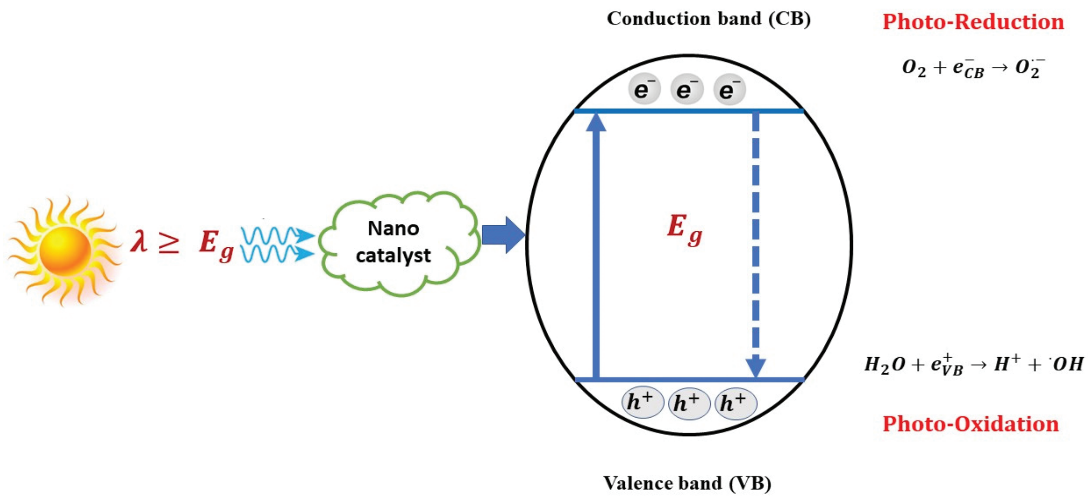

Fig. (1). Representation of reactions taking place at the surface of the catalyst. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

3. Neutralization of OH−groups by photo-holes which produces

OH° radicals:

$(H_2O \Leftrightarrow H^+ + OH^-)$ ads+ $h^{+VB} \rightarrow H^+ + OH^{\bullet}$ (3)

4. Neutralization of $O_2^{\circ-}$ by protons:

$O_2^{\circ-} + H^+ \rightarrow HO_2^{\circ}$ (4)

5. Transient hydrogen peroxide formation and dismutation of oxygen:

$2HO_2^{\circ-} \rightarrow H_2O_2 + O_2$ (5)

6. Decomposition of H_2O_2 and second reduction of oxygen:

$H_2O_2 + e^- \rightarrow OH^{\circ} + OH^-$ (6)

7. Oxidation of the organic reactant via successive attacks by hydroxyl radicals:

$R + OH^{\circ} \rightarrow R^{\bullet} + H_2O$ (7)

8. Direct oxidation by reaction with holes:

$R + h^+ \rightarrow R^{+\circ} \rightarrow$ Degraded Products (8)

As an example of the last process, holes can react directly with carboxylic acids generating CO_2:

$RCOO^- + h^+ \rightarrow R^{\bullet} + CO_2$ (9)

On the outer surface, the excited electron and hole take part in redox reactions with adsorbent species, such as water, hydroxide ion (OH^-), organic compounds, and oxygen. Charges interact directly with adsorbent pollutants but interaction with water is more likely because water molecules are more densely populated than contaminant molecules [53]. The oxidation of water or OH^- by the hole produces a hydroxyl root (•OH), which is a predominant and random oxidizer [65]. Photoreduction, photooxidation, and adsorption occur on or near the particle surface as shown in Fig. (**1**).

5. FACTORS AFFECTING PHOTOCATALYSIS

Various studies on photocatalysis of pesticides, organic pollutants, phenols, and their derivatives indicated that the photocatalytic degradation process is mainly affected by the following factors [66]:

5.1. pH of the Solution

The pH is a complex parameter because it correlates with the ionized state of the surface of the material. pH changes can affect the adsorption of contaminant molecules on the surfaces of the catalyst, which is assumed to be an important step for the oxidation of photocatalysis. The change in pH can lead to an improvement in the optical removal efficiency of organic pollutants in the presence of titanium dioxide without affecting the rate equation.

5.2. Catalyst Types and its Concentration

In various studies, it has been recognized that the rate of decomposition was found to increase with an increase in the concentration of the catalyst up to $5gL^{-1}$ and subsequent addition of the catalyst leads to a decrease in the rate of decomposition [67]. Heterogeneous photocatalytic reactions are known to show a proportional increase in photodegradation with the catalyst loading. The concentration of the catalyst in the photocatalytic water treatment system is directly proportional to the overall photocatalytic reaction rate [68].

Ahmed Khadem Abass (2018) studied the effect of catalyst type on photooxidation of benzene. The catalysts used were ZnO, Cu_2O, TiO_2 and Al_2O_3, which have a surface area of 38, 47.6, 50, and 55 g/m^2 according to the BET surface area analysis, respectively. It has been discovered that the rate of photooxidation of benzene increased with the increase in surface area of catalyst used and the minimum value (higher rate constant) with TiO_2 (high surface area) [69].

5.3. Effect of Light Wavelength and Intensity

The photochemical effects of light sources with various wavelength emitting ranges will have intense effects on the rate of photocatalysis reaction, depending on the types of photocatalysts crystalline phase (i.e., anatase, rutile or wurtzite) [70].

Light intensity is one of the few parameters that influence the degree of photocatalysis interaction on organic substrates. To achieve a high photocatalytic reaction rate, especially in water treatment, a relatively high light intensity is required.

5.4. Effect of Surface Area and Adsorption

Surface area is one of the most important aspects of nanostructured semiconductor photocatalysis. It is well known that as the size goes down on the nanometer regime, there is a gradual increase in surface area. Consequently, there is an increase in the percent degradation rate of pollutants [71]. More is the surface area available, more pollutant will be adsorbed over the surface, thus,directly increasing the degradation rate [72].

5.5. Composition and Concentration of Pollutant: Previous

Investigations indicated that the rate of photocatalytic reaction was dependent on the concentration of water pollutants. The concentration of pollutants is a very important parameter. It is noted that as the concentration of the combined solution increases, the rate of degradation decreases [73]. The reason for this behavior may be the increase in the extent of adsorption on the catalytic surface at the concentration of the primary compound which reduces catalytic activity [74].

5.6. Reaction Temperature

Several studies have been done on the photocatalytic reaction depending on the reaction temperature. It has been observed from various studies that there is a decrease in photocatalysis activity, with an increase in the reaction temperature [75].

6. TYPES OF PHOTOCATALYSIS REACTIONS

To categorize the existing approaches of photocatalysis, we present in Fig. (**2**) four classes of reactions. In the first category (Fig. **2a**) is the most successful photocatalysis, natural photosynthesis. An ingenious result of billions of years of evolution by Mother Nature, the process has been the main source of our energy supply. Carbohydrates are the key products of these reactions [76]. A variation of this reaction is shown in Fig. (**2b**), where microalgae perform reactions similar to those in plants but synthesize unique chemicals such as H_2 or other valuable chemicals (*e.g*., ethanol, butanol, glycerol, and isoprene) [76, 77]. When it comes to artificial photosynthesis systems, a great number of variations exist. They may be grouped into two general types as summarized in Figs. (**2c** and **2d**). When the reduction and oxidation reactions are not intentionally separated (Fig. **2c**), a system with the benefit of inherently low cost is obtained. Note that reactions involving both heterogeneous and homogeneous catalysts can be included in this category. A competing strategy is to physically separate the reduction and oxidation sites. A wired version of the last strategy is shown in Fig. (**2d**). But the wire is not essential here. A back-to-back wireless configuration falls in the same category, as well [78]. A key distinguishing feature of Figs. (**2c** and **2d**) is whether the reduction and oxidation sites are physically separated by a reasonable distance (greater than a few hundred nanometers) [79].

7. APPLICATION OF PHOTOCATALYSIS

Heterogeneous photocatalysis has proven to be a low-cost and sustainable technology for treating a mass of pollutants in air and water, including organic matter and heavy metals. In recent years, research efforts have been directed towards environmental cleaning and treatment of toxic waste, pollutants, and dye degradation [80, 81].

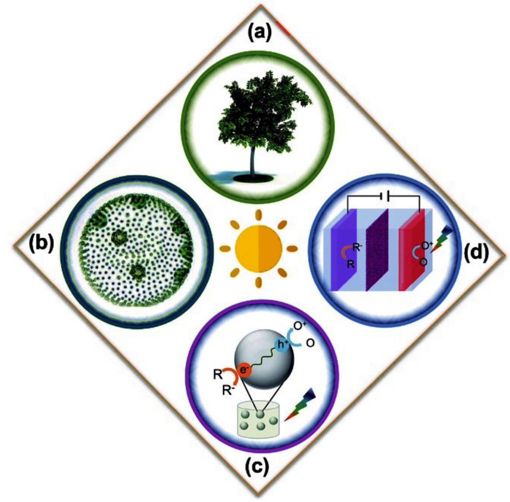

Fig. (2). Types of photocatalytic reactions. **a**) Natural photosynthesis in plants, **b**) photosynthesis by microalgae, **c**) nanoparticles photocatalysis, **d**) photoelectrocatalysis. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

7.1. Heavy Metals Removal

Heterogeneous photocatalysis has been widely used in removing heavy metals from wastewater such as Mercury (Hg), Selenium (Se), Chromium (Cr), Zinc (Zn), Lead (Pb), Cadmium (Cd), Arsenic (As), and Nickel (Ni). The photo-reducing ability of photocatalysis has been used to recover expensive metals from industrial effluents, such as Gold (Au), Platinum (Pt), and Silver (Ag) [81].

7.2. Destruction of Organic Pollutants

Organic compounds, such as alcohols, carboxylic acids, phenolic derivatives, or chlorinated aromatics, that may contaminate water in the form of 2,4,5 trichlorophenoxyacetic acid, 2,4,5 trichlorophenol, S-triazine herbicides and DDT can be also completely mineralized into non-toxic by-products (*e.g*., carbon dioxide, water, and simple mineral acids, herbicides, and pesticides) [31,82, 83].

7.3. Removal of Inorganic Pollutants

Inorganic species such as bromate, or chlorate, azide, halide ions, nitric oxide, palladium and rhodium species, and sulfur species can be decomposed with the appropriate catalyst. Metal salts, such as $AgNO_3$, HgCl, and organometallic compound (*e.g.* CH_3HgCl), can be removed from the water, as well as cyanide, thiocyanate, ammonia, nitrates, and nitrites [84, 85].

7.4. Water Disinfection

Water disinfection is Used to decontaminate the water from various microbes pollutant toxic for both humans and the environment i.e., *Streptococcus mutants, Streptococcus natuss, Streptococcus cricetus, Escherichia coli, Scaccharomycescerevisisas, Lactobacillus acidophilus,* poliovirus, Microcystin toxins, Chlorella Vulgaris, *etc* [57, 58, 86].

7.5. Air Purification

Room air cleaner, air conditioner, and indoor air cleaner for factories, and air purification can also be obtained, at least to a certain extent, at an illuminated surface coated with a semiconductor and this principle has been implemented for a variety of commercial applications, both indoors and outdoors [87].

7.6. Water Purification using Plasma and Photocatalytic Utilization by Employing NIR light

Plasmas on/in/with an aqueous solution has attracted much attention because of their possible applications for solving the environmental issue of water purification, which employs various types of electrical discharge methods such as arc discharges, corona discharges, rf discharges, dielectric barrier discharges, high voltage pulse discharges, and so on. Low temperature plasma can cause defects and oxygen vacancies on the catalyst surface to improve the catalytic efficiency [88]. The effect of treating the catalyst with low-temperature plasma under different atmospheres is different. Nanowires and nanoparticles of TiO_2 treated under a hot hydrogen atmosphere have better photocatalytic degradation of dye properties because of the presence of oxygen vacancies and Ti^{3+} forming an intermediate layer [89, 90]. In the last decade, the focused $NaYF_4$:Yb,Er/Tm agents have been successfully applied to advanced assembly materials. For example, the preparation of the $NaYF_4$:Yb,Tm/CdS composite has been reported, and the NIR photocatalytic activity has been investigated by degrading Rhodamine B and methylene blue [91, 92].

8. RECENT ADVANCES AND FUTURE CHALLENGES

Photocatalysis progressed from explorative research to commercial development. A look at the recent literature reveals a steady flow of over 1300 international patents annually in this field for various applications from 2000, most of which were concerned with pollution control and based on the use of TiO_2 [50]. With more research and development of materials, new applications of nanomaterial-based photocatalysts will emerge. One of the products of good research is new knowledge that enables new technologies. The final review focus will affirm the prospects and challenges of using photocatalysts to clean and treat the environment. One of the main challenges for the scientific community concerned with photocatalytic research is to increase the spectral sensitivity of the photocatalysts to visible light, which forms the bulk of the solar radiation. One must take into account the fact that environmental catalytic cleaning is only suitable for low-level pollutants because the amount of UV photons is limited in both solar light and interior lighting [88]. Another major challenge is that TiO_2 nanoparticles not only destroy all organic matter but also the organic matrix in which nanoparticles are included. This limits its application to inorganic environments. TiO_2 nanoparticles are expected to have a minimal negative impact on both human health and the environment as they are usually fixed in/to substrate material [93]. There are currently no regulations regarding the use of nanoparticles for water treatment, but standards for test approaches for photocatalytic water purification are under development. Ternary metal oxides could also be promising photoelectrode materials for water splitting and organic synthesis [94].

CONCLUSION

While developing various aspects of nanotechnology, the broad environmental impacts of this must also be taken into account. These considerations may include models for identifying potential benefits of reducing or preventing pollutants from industrial sources. Nanotechnology has great potential for the continuous improvement of technologies related to environmental protection. The current review provides more evidence of this issue and tried to address what all the potential environmental impacts of the technology might be. Therefore, the discussion in the review indicates that a cleaner, greener environment, and a renewable and sustainable energy economy can be achieved through photocatalysis. To enhance the feasibility of photocatalysis soon, several major technical constraints ranging from catalyst development to reactor design and process improvement should be addressed.

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AVAILABILITY OF DATA AND MATERIALS

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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REFERENCES

[1] Mansoori GA, Rohani BT, Ahmadpour A, Eshaghi Z. Environmental Application of Nanotechnology. Ann Rev Nano Res 2008; 2: 1-73.

[2] Abu-Dief, A M.;Abdelbaky, MSM ; Martínez-Blanco, D , Amghouz Z; García-Granda, S, Effect of chromium substitution on the structural and magnetic properties of nanocrystalline zinc ferrite, *Mater. Chem. Phys.* **2016**,174 (1)164–171. http://dx.doi.org/10.1016/j.matchemphys.2016.02.065

[3] Abu-Dief, A M; Nassar, I F; Elsayed, WH. Magnetic $NiFe_2O_4$ nanoparticles: efficient, heterogeneous and reusable catalyst for synthesis of acetylferrocene chalcones and their anti-tumour activity, *Appl. Organomet. Chem.*, **2016,** 30, 917-923. http://dx.doi.org/10.1002/aoc.3521

[4] El-Remaily, M A A A and Abu-Dief, A M; Rafat M. El-Khatib A robust Synthesis and Characterization for Superparamagnetic $CoFe_2O_4$ Nanoparticles as an Efficient and Reusable Catalyst for Green Synthesis of Some Heterocyclic Rings, *Appl. Organomet. Chem.*, **2016**, 30, 1022–1029. https://doi.org/10.1002/aoc.3536.

[5] Ibrahim EMM, Abdel-Rahman LH, Abu-Dief AM, *et al.* Electric, thermoelectric and magnetic characterization of γ-Fe_2O_3 and Co_3O_4 nanoparticles synthesized by facile thermal decomposition of metal-Schiff base complexes. Mater Res Bull 2018; 99: 103-8. http://dx.doi.org/10.1016/j.materresbull.2017.11.002

[6] Mohamed WS, Alzaid M, Abdelbaky MSM, Amghouz Z, García-Granda S, Abu-Dief AM. Impact of Co^{2+} Substitution on Microstructure and Magnetic Properties of $Co_xZn_{1-x}Fe_2O_4$ Nanoparticles. Nanomaterials (Basel) 2019; 9(11): 1602. http://dx.doi.org/10.3390/nano9111602 PMID: 31718062

[7] Al-Saeedi SI, Abdel-Rahman LH, *et al.* Catalytic Oxidation of Benzyl Alcohol Using Nanosized Cu/Ni Schiff-Base Complexes and Their Metal Oxide Nanoparticles. Catalysts 2018; 8(10): 452. http://dx.doi.org/10.3390/catal8100452

[8] Ali El-Remaily MAEAA, Abu-Dief AM, Elhady O. Green synthesis of TiO2 nanoparticles as an efficient heterogeneous catalyst with high reusability for synthesis of 1,2-dihydroquinoline derivatives Appl Organomet Chem 2019; 33(8): 5005.

[9] Mahmoud WS, Abu-Dief AM. Synthesis, characterization and photocatalysis enhancement of Eu2O3-ZnO Mixed oxide nanoparticles J Phys Chem Solids 2018; 116: 375-85. http://dx.doi.org/10.1016/j.jpcs.2018.02.008

[10] Abu-Dief AM, Mahmoud WS. α-Bi2O3 nanorods:synthesis, characterization and UV-photocatalytic activity Mater Res Express 2017; 4: 035039. http://dx.doi.org/10.1088/2053-1591/aa6712

[11] Abde-Rahman LH, Abu-Dief AM, El-Khatib RM, *et al.* Sonochemical synthesis, structural inspection and semiconductor behavior of three new nano sized Cu(II), Co(II) and Ni(II) chelates based on tri-dentate NOO imine ligand as precursors for metal oxides. Appl Organomet Chem 2018; 32(3): 4174. http://dx.doi.org/10.1002/aoc.4174

[12] Abu-Dief AM, Abdel-Mawgoud AAH. Functionalization of Magnetic Nanoparticles for Drug Delivery. SF J Nanochem and Nanotech 2018; 1(1): 1-6.

[13] Herrmann JM. Fundamentals and misconceptions in photocatalysis. . J Photochem Photobiol 2010; 216: 85-93. http://dx.doi.org/10.1016/j.jphotochem.2010.05.015

[14] Anandan S, Yoon M. Photo-catalytic activities of the nano-sized TiO2-supported Y-zeolites,. J Photochem Photobiol Chem 2003; 4: 5-18. http://dx.doi.org/10.1016/S1389-5567(03)00002-9

[15] Gayaa UI, Abdullaha AH. Heterogeneous photo-catalytic degradation of organic contaminants over titanium dioxide: A review of fundamentals, progress and problems. J Photochem Photobiol Chem 2008; 9: 1-12. http://dx.doi.org/10.1016/j.jphotochemrev.2007.12.003

[16] Bruner L, Kozak J, Elektrochem Z. Z Elektrochem Angew Phys Chem 1911; 17: 354-60.

[17] [Emil Baur & A. Perret, Über die Einwirkung von Licht auf gelöste Silbersalze in Gegenwart von Zinkoxyd. Helv Chim Acta 1924; 7(1): 910-5. http://dx.doi.org/10.1002/hlca.192400701109

[18] Milenova K, Stambolova I, Blaskov V, Eliyas AE. The effect of introducing copper dopant on the photo-catalytic activity of ZnO nanoparticles. TechMetal 2013; 48: 259-64.

[19] Ravelli D, Dondi D, Fagnoni M, Albini A. Photocatalysis. A multifaceted concept for green chemistry. Chem Soc Rev 2009; 38(7): 1999-2011. http://dx.doi.org/10.1039/b714786b PMID: 19551179

[20] Mohapatra DP, Brar SK, Picard P, Tyagi RD. Preparation of a New Class of Whey-Stabilized ZnO Nanoparticles for Degradation of Bisphenol A in Water. Sci Adv Mater 2013; 5: 57. http://dx.doi.org/10.1166/sam.2013.1431

[21] Barnes RJ, Molina JR. Comparison of TiO_2 and ZnO nanoparticles for photo-catalytic degradation of methylene blue and the correlated inactivation of grampositive and gram-negative bacteria. Nanopart Res 2013; 15: 1432. http://dx.doi.org/10.1007/s11051-013-1432-9

[22] Hupka J, Zaleska A, Janczarek M, Kowalska E, Górska P, Aranowski R. UV/Vis light-enhanced photocatalysis for water treatment and protection. In: Twardowska I, Allen HE, Häggblom MM, Stefaniak S (Eds). Soil and Water Pollution Monitoring, Protection and Remediation. 2006; 3: 23.

[23] Angew HK. Semiconductor photocatalysismechanistic andsynthetic aspects. Reviews 2013; 52(3): 812-47.

[24] Kansal S, Kaur N, Singh S. Photocatalytic degradation of two commercial reactive dyes in aqueous phase using nanophotocatalysts. Nanoscale Res Lett 2009; 4(7): 709-16. http://dx.doi.org/10.1007/s11671-009-9300-3 PMID: 20596421

[25] Moroz P, Boddy A, Zamkov M. Challenges and Prospects of Photocatalytic Applications Utilizing Semiconductor Nanocrystals. Front Chem 2018; 6: 353. http://dx.doi.org/10.3389/fchem.2018.00353 PMID: 30159309

[26] Kanhere P, Zheng J. Visible light driven photocatalytic hydrogen evolution and photophysical properties of Bi3D doped NaTaO3 Intr J Hyd Ener 2012; 37: 4889-96. http://dx.doi.org/10.1016/j.ijhydene.2011.12.056

[27] Wang X. Nanomaterials as sorbents to remove heavy metal ions in wastewater treatment. J Environ Anal Toxicol 2012; 2: 7.

[28] Baruah S, Mahmood MA, Myint MT, Bora T, Dutta J. Enhanced visible light photocatalysis through fast crystallization of zinc oxide nanorods. Beilstein J Nanotechnol 2010; 1: 14-20. http://dx.doi.org/10.3762/bjnano.1.3 PMID: 21977391

[29] Saber A, Rasul M, Martens W. Recent developments in photocatalytic degradation of pesticides and phenols in storm and wastewater effluent. Proceedings of the ERE 2010 Conference: Transitions to a Sustainable Future. 1-5.

[30] Tyagi PK, *et al.* Nanomaterials Use in Wastewater Treatment International Conference on Nanotechnology and Chemical Engineeering (ICNCS'2012). December 21-22, 2012; Bangkok (Thailand).

[31] Saber A. Influence of parameters on the heterogeneous photocatalytic degradation of pesticides and phenolic contaminants in wastewater: a short review. J Environ Manage 2011; 92(3): 311-30. http://dx.doi.org/10.1016/j.jenvman.2010.08.028 PMID: 20950926

[32] Lazar MA, Varghese S, Nair SS. Photocatalytic water treatment by titanium dioxide: recent updates. Catalysts 2012; 2: 572-601. http://dx.doi.org/10.3390/catal2040572

[33] Ibhado AO, Fitzpatrick P. Heterogeneous Photocatalysis: recent advances and applications. Catalysts 2013; 3: 189-218. http://dx.doi.org/10.3390/catal3010189

[34] Evgenidou E, Fytianos K, Poulios I. Semiconductor-sensitized photo-degradation of Dichlorvos in water using TiO2 and ZnO as catalysts Appl Catal B 2005; 59: 81-9. http://dx.doi.org/10.1016/j.apcatb.2005.01.005

[35] Vinodgopal K, Bedja I, Kamat PV. .Nanostructured semiconductor films for photocatalysis. photoelectrochemical behavior of SnO2/TiO2 composite systems and its role in photocatalytic degradation of a textile azo dye Chem Mater 1996; 8: 2180-7. http://dx.doi.org/10.1021/cm950425y

[36] Fox MA, Dulay M. Heterogeneous Photocatalysis. Catal Rev 1995; 83: 341-57.

[37] Dobbs RA, Wang L, Govind R. Sorption of toxic organic compounds on wastewater solids: correlation with fundamental properties. fnviron. Sci Techno 1989; 23: 1092-7. http://dx.doi.org/10.1021/es00067a004

[38] Abu-Dief, A M; Essawy, AA; Diab, AK; Mohamed,W S, Facile synthesis and characterization of novel Gd_2O_3–CdO binary mixed oxide nanocomposites of highly photocatalytic activity for wastewater remediation under solar illumination*, J. Phys. Chem. Solids*, **2021**, 148, 109666. http://dx.doi.org/10.1016/j.jpcs.2020.109666

[39] Houas A, Lachhe H. Photo-catalytic degradation pathway of methylene blue in water. Appl Catal B 2001; 31: 145-57.

[40] Chih MM, Gui BH, Lee SC. Facile Synthesis of Tin Dioxide Nanoparticles for Photocatalytic Degradation of Congo Red Dye in Aqueous Solution. Catalysts 2020; 10: 792. http://dx.doi.org/10.3390/catal10070792

[41] Sathiyanarayanan S, Ravi PE, Ramesh A. Applications of Zinc Oxide nanorods as photo-catalyst for the decontamination of imidacloprid and spirotetramat residues in water. Open Catalysis Journal 2009; 2: 24-32. http://dx.doi.org/10.2174/1876214X00902010024

[42] Ali A, Muhammad A. Doped metal oxide (ZnO) and photocatalysis: A Review. J P I Ch E 2012; 40(1): 11-9.

[43] Muszkat L, Feigelson L, Bir L, Muszkat KA. Photocatalytic degradation of pesticides and bio-molecules in water. Pest Manag Sci 2002; 58(11): 1143-8. http://dx.doi.org/10.1002/ps.578 PMID: 12449534

[44] Xiao X, Ma X-L, Liu Z-Y, *et al.* Degradation of rhodamine B in a novel bio-photoelectric reductive system composed of Shewanella oneidensis MR-1 and Ag_3PO_4. Inter 2019; 126: 560-7. PMID: 30852443

[45] Dashairya L, Mehta A, Saha P, Basu S. Visible-light-induced enhanced photocatalytic degradation of Rhodamine-B dye using $Bi_xSb_{2-x}S_3$ solid-solution photocatalysts. J Colloid Interface Sci 2020; 561: 71-82. http://dx.doi.org/10.1016/j.jcis.2019.11.118 PMID: 31812868
[46] Santhosh C, Malathi A, Daneshvar E, Kollu P, Bhatnagar A. Photocatalytic degradation of toxic aquatic pollutants by novel magnetic 3D-TiO2@HPGA nanocomposite. Sci Rep 2018; 8(1): 15531. http://dx.doi.org/10.1038/s41598-018-33818-9 PMID: 30341353
[47] Dhandole LK, Kim SG, Bae HS, *et al.* Simultaneous and synergistic effect of heavy metal adsorption on the enhanced photocatalytic performance of a visible-light-driven RS-TONR/TNT composite. Environ Res 2020; 180108651 http://dx.doi.org/10.1016/j.envres.2019.108651 PMID: 31648071
[48] Ebenazer A, Vijayan P, Sampathkumar N, *et al.* Photocatalytic degradation of organophosphorus pesticide using semiconductor-sensitized composite in natural water: effect of oxidants. Appl Phys, A Mater Sci Process 2020; 126: 186. http://dx.doi.org/10.1007/s00339-020-3338-6
[49] Ba-Abbada MM, *et al.* Solar photocatalytic degradation of environmental pollutants using ZnO prepared by Sol-Gel: 2, 4-Dichlorophenol as Case Study. Int J Ther Environ Eng 2010; 1(1): 37-42. http://dx.doi.org/10.5383/ijtee.01.01.006
[50] Baruah S, Dutta J. Nanotechnology applications in pollution sensing and degradation in agriculture: a review. Environ Chem Lett 2009; 7: 191-204. http://dx.doi.org/10.1007/s10311-009-0228-8
[51] Samsun Nahar Md. Photocatalytic degradation of organic pollutants over visible light active plasmonic Ag nanoparticle loaded Ag2SO3 photocatalysts, J Photochem Photobiol Chem 2019; 375: 191-200. http://dx.doi.org/10.1016/j.jphotochem.2019.02.025
[52] Gupta NK, Ghaffari Y, Kim S, Bae J, Kim KS, Saifuddin M. Photocatalytic Degradation of Organic Pollutants over MFe2O4 (M = Co, Ni, Cu, Zn) Nanoparticles at Neutral pH Sci Rep 2020; 10(1): 4942. http://dx.doi.org/10.1038/s41598-020-61930-2 PMID: 32188893
[53] Akpan UG, Hameed BH. anomaterial for Photocatalysis and their application in environmental clean-up photocatalysts: A review. J Hazard Mater 2009; 170: 520-9. http://dx.doi.org/10.1016/j.jhazmat.2009.05.039 PMID: 19505759
[54] Konstantinou IK, Albanis TA. Review Photocatalytic transformation of pesticides in aqueous titanium dioxide suspensions using artificial and solar light: intermediates and degradation pathways. Appl Catal B 2002; 1310: 1-17.
[55] Xiong B, Zhou A, Zheng G, *et al.* Photocatalytic degradation of endosulfan in contaminated soil with the elution of surfactants. J Soils Sediments 2015; 15: 1909-18. http://dx.doi.org/10.1007/s11368-015-1139-x
[56] Fujishima A, Honda K. Electrochemical photolysis of water at a semiconductor electrode. Nature 1972; 238(5358): 37-8. http://dx.doi.org/10.1038/238037a0 PMID: 12635268
[57] Hoffmann MR. Environmental applications of semiconductor photocatalysis. Chem Rev 1995; 95(1): 69-96. http://dx.doi.org/10.1021/cr00033a004
[58] Barber J. Photosynthetic energy conversion: natural and artificial. Chem Soc Rev 2009; 38(1): 185-96. http://dx.doi.org/10.1039/B802262N PMID: 19088973
[59] Al-Qaradawi S, Salman SR. Photo-catalytic degradation of methyl orange as a model compound. J Photochem Photobiol Chem 2002; 148(1-3): 161-8. http://dx.doi.org/10.1016/S1010-6030(02)00086-2
[60] Xue Y, Tian D, Zeng C, Fu Y, Li K. Effect of Fe doping concentration on photocatalytic performance of CeO2 from DFT insight into analysis, AIP Adv 2019; 9125341 http://dx.doi.org/10.1063/1.5124317
[61] Yoon M, Negi DP. Photoinduced electron transfer in some photosensitive molecules-incorporated semiconductor/zeolites: New photocatalytic systems. Proc. Indian. Acad Sci Chem Sci 2002; 114(6): 593-602. http://dx.doi.org/10.1007/BF02708853
[62] Tan TK, Khiew P. Photodegradation of phenol red in the presence of ZnO Nanoparticles. World Acad Sci Eng Technol 2011; 5(7): 613-8.
[63] DongTianab , DexinZhang , YunchangFu ChunhuaZeng , KongzhaiLi , HuaWang , YafangTian . YufeiXuea. The mechanism of photocatalyst and the effects of co-doping CeO2 on refractive index and reflectivity from DFT calculation Comput Mater Sci 2019; 158: 197-208. http://dx.doi.org/10.1016/j.commatsci.2018.11.003
[64] Giahi M, Ghanbar F. Photocatalytic degradation of Triton X-100 by Zinc oxide Nanoparticles. J Phys Theor Chem 2010; 7(3): 189-93.
[65] Prabha I. Photocatalytic performance of nanocatalyst for the effective removal of dye in the wastewater. Chem Sci Trans 2013; 2(1): 220-4.
[66] Chong MN, Jin B, Chow CW, Saint C. Recent developments in photocatalytic water treatment technology: a review. Water Res 2010; 44(10): 2997-3027. http://dx.doi.org/10.1016/j.watres.2010.02.039 PMID: 20378145
[67] Malato S, Blanco J, Ritcher C, Fernández P, Maldonado MI. Solar photocatalytic mineralization of commercial pesticides: Oxamyl. Sol Energy Mater Sol Cells 2000; 64: 1-14. http://dx.doi.org/10.1016/S0927-0248(00)00037-4
[68] Neppolian B, Choi HC, Sakthivel S, Arabindoo B, Murugesan V. Solar/UV-induced photocatalytic degradation of three commercial textile dyes. J Hazard Mater 2002; 89(2-3): 303-17. http://dx.doi.org/10.1016/S0304-3894(01)00329-6 PMID: 11744213
[69] Abass AK. Effect Type of Solvent, Type of Catalyst and Power of Lamp on Photo Oxidation of Benzene. Journal of University of Babylon for Engineering Sciences 2018; 26(10): 197-206.
[70] Cataño FA, Valencia S, Hincapié EA, Restrepo G. A Comparative study between TiO2 and ZnO Photocatalysis: photocatalytic degradation of Cibacron Yellow Fn-2r Dye. Lat Am Appl Res 2012; 42: 33-8.
[71] Barhon Z, Elbaraka N, Saffaj N, *et al.* Photocatalysis–Membrane Separation Coupling Reactor: Removal of Organic Pollutants from Water. Scientific Study & Research: Chemistry & Chemical Engineering, Biotechnology, Food industry. 13(1): 105-8.
[72] Gogate PR, Pandit AB. Sonophotocatalytic Reactors for Wastewater Treatment: A Critical Review. AIChE J 2004; 50(5): 1051. http://dx.doi.org/10.1002/aic.10079
[73] Shah I, Huang CP, Chen JG, Doren D, Barteau M. Semiconductor Metal Oxide Nanoparticles for Visible Light Photocatalysis.
[74] Islam NM, Chatterjee M, Ikushima Y, Yokoyama T, Kawanami H. Development of a novel catalytic membrane reactor for heterogeneous catalysis in supercritical CO_2. Int J Mol Sci 2010; 11(1): 164-72. http://dx.doi.org/10.3390/ijms11010164 PMID: 20162008
[75] Madhusudhana N, Yogendra K, Mahadevan KM. Photocatalytic Degradation of Violet GL2B Azo dye by using Calcium Aluminate Nanoparticle in presence of Solar light. Research Journal of Chemical Sciences 2012; 2(3): 72-7.
[76] Melis A. Photosynthesis-to-fuels: from sunlight to hydrogen, isoprene, and botryococcene production. Energy Environ Sci 2012; 5: 5531. http://dx.doi.org/10.1039/C1EE02514G
[77] Radakovits R, Jinkerson RE, Darzins A, Posewitz MC. Genetic engineering of algae for enhanced biofuel production. Eukaryot Cell 2010; 9(4): 486-501. http://dx.doi.org/10.1128/EC.00364-09 PMID: 20139239
[78] Reece SY, Hamel JA, Sung K, *et al.* Wireless solar water splitting using silicon-based semiconductors and earth-abundant catalysts. Science 2011; 334(6056): 645-8. http://dx.doi.org/10.1126/science.1209816 PMID: 21960528
[79] Ampelli C, Centi G, Passalacqua R, Perathoner S. Synthesis of solar fuels by a novel photoelectrocatalytic approach. Energy Environ Sci 2010; 3: 292. http://dx.doi.org/10.1039/b925470f
[80] Madhusudhana N, Yogendra K, Mahadevan KM, Naik S. Photocatalytic Degradation of Coralene Dark Red 2B Azo Dye Using Calcium Zincate Nanoparticle in Presence of Natural Sunlight: An Aid to Environmental Remediation. Int J Chem Eng Appl 2011; 2(4): 294-8.

http://dx.doi.org/10.7763/IJCEA.2011.V2.120
[81] Mohanraj VJ, Chen Y. Nanoparticles –. RE:view 2006; 5: 561-73.
[82] Meng J, Yang B, Zhang Y, Dong X, Shu J. Heterogeneous ozonation of suspended malathion and chlorpyrifos particles. Chemosphere 2010; 79(4): 394-400.
http://dx.doi.org/10.1016/j.chemosphere.2010.02.008 PMID: 20176393
[83] Verma A, Dixit D. Photocatalytic degradability of insecticide Chlorpyrifos over UV irradiated Titanium dioxide in aqueous phase. Int J Environ Sci 2012; 3(2): 743-55.
[84] Šíma J, Hasal P. Photocatalytic Degradation of Textile Dyes in aTiO2/UV System Chem Eng Transation 2013; 32: 79-84.
[85] Turchi CS. Photocatalytic Degradation of Organic Water Contaminants: Mechanisms Involving Hydroxyl Radical Attack. J Catal 1990; 192: 178-92.
http://dx.doi.org/10.1016/0021-9517(90)90269-P
[86] Ni M. A review and recent developments in photocatalytic water-splitting using TiO2 for hydrogen production Renew Sustain Energy Rev 2007; 11: 401-25.
http://dx.doi.org/10.1016/j.rser.2005.01.009
[87] Ullah I, Ali S, Hanif MA, Shahid SA. Nanoscience for environmental remediation: A Review. Int J Chem Biochem Sci 2012; 2: 60-77.
[88] Pylnev M, Chang W-H, Wong M-S. Shell of black titania prepared by sputtering TiO2 target in H2 + Ar plasma Appl Surf Sci 2018; 462: 285-90.
http://dx.doi.org/10.1016/j.apsusc.2018.08.103
[89] Zheng Z, Huang B, Lu J, *et al.* Hydrogenated titania: synergy of surface modification and morphology improvement for enhanced photocatalytic activity. Chem Commun (Camb) 2012; 48(46): 5733-5.
http://dx.doi.org/10.1039/c2cc32220j PMID: 22552253
[90] Li Y, Wang W, Wang F, *et al.* Enhanced Photocatalytic Degradation of Organic Dyes *via* Defect-Rich TiO2 Prepared by Dielectric Barrier Discharge Plasma Nanomaterials (Basel) 2019; 9(5): 720.
[91] Li, C, Wang F, Zhu J, Yu JC. NaYF4: Yb, Tm/CdS composite as a novel near-infrared-driven photocatalyst. Appl Catal B 2010; 100(3-4): 433-9.
http://dx.doi.org/10.1016/j.apcatb.2010.08.017
[92] Zhang Junjie, Zhao Suling, Zheng X, Zhang Ligang, Zuo Pengfei. Near-infrared light-driven photocatalytic NaYF4:Yb,Tm@ZnO core/shell nanomaterials and their performance RSC Adv 2019; 9: 3688-92.
[93] Zhu C, Wang L, Kong L, *et al.* Photocatalytic degradation of AZO dyes by supported TiO2 + UV in aqueous solution. Chemosphere 2000; 41(3): 303-9.
http://dx.doi.org/10.1016/S0045-6535(99)00487-7 PMID: 11057591
[94] He HC, Liao AZ, Guo WL, *et al.* State-of-the-art progress in the use of ternary metal oxides as photoelectrode materials for water splitting and organic synthesis. Nano Today 2019; 28100763
http://dx.doi.org/10.1016/j.nantod.2019.100763