A mini overview of miscellaneous uses of TiO_2 based nanomaterials

Kristi Priya Choudhury
Nano Research Centre

Neogi, Newton
Nano Research Centre

Sabbir Hossain Nipu
Nano Research Centre

Tahzib Ibrahim Protik
Nano Research Centre

https://doi.org/10.5109/5909095

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 8, pp.221-227, 2022-10-20. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
バージョン：

A mini overview of miscellaneous uses of TiO_2 based nanomaterials

Kristi Priya Choudhury[1, 2*], Newton Neogi[1, 2], Sabbir Hossain Nipu[1, 2], Tahzib Ibrahim Protik[1, 2]
[1]Nano Research Centre, Bangladesh
[2]Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh
*Corresponding author email: kristi021@student.sust.edu

Abstract: *TiO_2 nanoparticles (NPs) are very necessary for the uses that they have in a variety of fields. Several different industries are now showing a significant amount of interest in distinct types of TiO_2 NPs, as well as their production, characterization, and significant applications. TiO_2 NPs will benefit greatly from the development of improved synthetic pathways and better characterization techniques as a result of their quick translation into industries, the fabrication of a large number of valuable goods, and their implications for the expansion of the economy. In this study, we will discuss the many methodologies for the synthesis of TiO_2 nanomaterials, the advancements that have been made in characterization methods, as well as the various unique industrial and other important application domains.*

Keywords: Antibacterial property; biosensing; food packaging; photocatalysis; TiO_2.

1. INTRODUCTION

TiO_2 NPs may be used in a variety of industries and applications. TiO_2 NPs possess a variety of advantageous and intriguing qualities; thus, we investigate how they might be used in a few industries [1]. TiO_2 may be combined with other semiconductors to enhance the absorption of UV and visible light. TiO_2 NPs has thin band structure is responsible for this. TiO_2 nanomaterials may become more effective in different sectors (Table 1). These can act as photocatalysis as a result of their ability to aggregate photogenerated electrons and holes on diverse semiconductor surfaces, leading to an increase in the electrons' redox reactions. A consensus exists that anatase TiO_2 is the most effective photocatalyst. Despite the fact that TiO_2 already has a high photocatalytic activity, several attempts have been made to boost this activity by modifying either the surface or bulk properties of the material [2][3]. These modifications include adding metals to the surface, chelating the surface, and combining two different semiconductors into a single material. Recently, it has become standard practice to use UV-resistant polymers as substrates for nanoscale titanium dioxide photocatalysts. These polymers include polyethylene oxide, polystyrene dabs, and cellulose microspheres [4]. It is possible to enhance the photocatalytic activity of nano-TiO_2 photocatalyst. If photosynthesis were to increase, more food for humans may be generated. On food packaging film, various amounts of photocatalytic antimicrobial TiO_2 NPs [5] may be applied. As a result, the film may be used to keep germs at away. Nano-TiO_2 has been used as a potential nano-fertilizer or nano-pesticide [6] to increase agricultural yield, decrease crop diseases, and reduce the amount of hazardous organic solvents in agrichemicals. *Escherichia coli* and *Staphylococcus aureus*, Gram-positive and Gram-negative foodborne pathogenic bacteria, were tested against PBAT/TiO_2 nanocomposite films to better understand the zone of inhibition [7]. As a food source and implant material, TiO_2 nanocomposite may potentially enhance biological applications, such as the delivery of NPs for the formation of new cells [8]. In recent years, academics from a variety of disciplines, including physics, chemistry, and material science, has become interested in TiO_2 Nanowires. When porous TiO_2 NPs are coated with polyethylenimine (PEI), it is possible to investigate the viability of using titanium dioxide's photocatalytic potential, which is to accomplish ultraviolet (UV) light-driven drug release PEI. The NPs are modified using PEI to obtain this outcome. By inhibiting the early drug release from PEI on the surface of multifunctional porous TiO_2 NPs [9] [10], an optimum circulation time may be delivered to cancer cells. For this, the channel may be blocked. In the future, TiO_2 NPs and nanocomposites may potentially be employed as glucose biosensors [11]. Researchers have designed a dye sensitized TiO_2 photodetector that may function as a disposable colorimetric biosensor. This photodetector was developed for a DNA detection method. As a consequence, TiO_2 may be used in a variety of industries and fields.

2. WATER TREATMENT SECTORS

Using TiO_2 and other n-type semiconductor metal oxides, it is feasible to eliminate organic pollutants from water by photolysis [12]. On the basis of the band placements of the Normal Hydrogen Electrode (NHE), organic contaminants can be eliminated. Nano-TiO_2 has low toxicity, high compound safety, and cheap cost make it a viable alternative for water and wastewater treatment [13]. TiO_2 nanocomposites are used in wastewater treatment by dye adsorption and dye degradation [14]. Various TiO_2 nanomaterials, for example, SWCNT/TiO_2 ultrathin film [15], Ag-Coated SiO_2@TiO_2 Core-Shell Nanocomposites [16], TiO_2–zeolite nanocomposite, [17] Au/TiO_2 NPs [18], TiO_2/graphene-based nanocomposites [19], TiO_2–Montmorillonite/ Polythiophene-SDS nanocomposites [20], Pt/TiO_2Nanocomposites [21], clay-TiO_2 nanocomposites [22] are used in wastewater treatment. Nanodot MoS_2@3DOM TiO_2 composites has photocatalytic applications which made it useful in water treatment [23]. The ultrathin SWCNT/TiO_2 film is used to treat emulsified wastewater from industry and daily life. Additionally, it is utilized to decontaminate crude oil and gasoline [15]. When exposed to ultraviolet radiation, SiO_2@TiO_2 core-shell nanoparticles may degrade phenol and methylene blue [16]. This is essential for wastewater treatment. Regarding the photocatalytic elimination of water pollutants, the TiO_2–zeolite nanocomposite relies mostly on adsorption. As a result, it is an excellent approach to eliminate trace and untreated dye components at the conclusion of the dye manufacturing wastewater cleaning process. [17]. PVA/PAA/GO-

COOH@TiO_2 membranes are also capable of effectively treating dye wastewater [24]. The nanocomposite of TiO_2–rGO–AC is also utilized to remediate wastewater because it is effective in degrading tetracycline in water [25]. TiO_2 nanoparticles are gaining popularity as a photocatalyst due to their excellent physical and chemical safety, low cost, high photocatalytic activity, and environmental friendliness [26]. Additionally, TiO_2 nanoparticles leave behind a negligible quantity of carbon. Ultraviolet light might be absorbed by TiO_2 nanoparticles because their band gap energy is quite high. TiO_2 nanoparticles may be employed as a photocatalyst [1] because to the rapid return of photogenerated electrons and positive holes to their original states. When TiO_2 is combined with other semiconductors, the quantity of ultraviolet to visible light that may be absorbed might increase. This is because of how TiO_2 is manufactured. This makes it feasible for photogenerated electrons and holes to congregate on the surfaces of certain semiconductors. This may therefore increase the photocatalytic activity of TiO_2 nanomaterials by accelerating the redox process between electrons and holes [2]. Therefore, one of the most prevalent methods for enhancing the performance of photocatalysts [27] is to minimize the energy gap of TiO_2 to increase its ability to absorb visible light. The majority of individuals believe that anatase TiO_2 is the most effective photocatalyst. Numerous individuals have attempted to improve TiO_2's photocatalytic performance by modifying either its surface qualities or its bulk properties. These modifications include doping, metal deposition, surface chelation, and the combination of two distinct kinds of semiconductors [3]. Different types of TiO_2 nanomaterials, for example, TiO_2/clay nanocomposite [28], Nanosized TiO_2 [3], TiO_2/hydrogel nanocomposite [29], Graphene/Pd/TiO_2 Nanocomposites [30], Polypropylene reduced graphene oxide-TiO_2 nanocomposite [31], ZnO/TiO_2/Ag_2O nanocomposite [32], TiO_2 nanofillers [33], Carbon Nanotube/Titanium Dioxide Nanocomposites [34], SiO_2@TiO_2 Core-Shell Nanocomposite [35], Ag/TiO_2 nanocomposites [36], C–TiO_2 doped cellulose acetate nanocomposite film [27] TiO_2-ITO and TiO_2-ZnO nanocomposites [37], Hexagonal boron nitride -TiO_2 Nanocomposite [38], Au/Ag-TiO_2 aerogel nanocomposites [39], gold capped TiO_2 NPs [40], WO_3/TiO_2 Nanocomposites [41] etc. can exhibit photocatalytic property. TiO_2 nanomaterials are utilized in removing arsenate, arsenite [13], HgO [42], Pb (II), Cu (II) [43], Hg (II) [44] from ground water. Because TiO_2 nanoparticles have such a wide surface area, they may remove heavy metals from groundwater. For example, photocatalytic reduction of Hg (II) from water may be accomplished using these nanomaterials in the removal of heavy metals from groundwater. Temperature and pH also play a role in these adsorption processes. When the pH is low enough, arsenate can be eliminated [43][44].

3. FOOD SECTORS

TiO_2 NPs can develop photosynthesis rate of plant by promoting the synthesis of chlorophyll A [45]. Nanomaterials based on TiO_2 can be utilized in food packaging [46]. TiO_2 nanocomposites such as SSPS/TiO_2 nanocomposites showed fantastic antimicrobial action against *Staphylococcus aureus*. So, SPSS/TiO_2 nanocomposites containing 7 wt. % of TiO_2 can be utilized for food packaging [47]. Copper-doped TiO_2 NPs with reduced graphene oxide (Cu_2O-TiO_2/rGO) nanocomposites may also be more effective at killing bacteria when exposed to visible light, with a larger zone of inhibition and a lower minimum inhibitory concentration for both Gram-positive and Gram-negative microbes. Because of this, these nanocomposites could be used to package food. Nanomaterials made from TiO_2 can kill bacteria and other microorganisms [48][49]. TiO_2 NPs, gold capped TiO_2 nanocomposites, and V doped TiO_2 NPs has antibacterial effect against two kinds of bacteria, *E. coli* and *B. megaterium* [50]. TiO_2 NPs has been incorporated in numerous biomaterials and it can induce antimicrobial activity [51]. PEG-PU-TiO_2 polymer nanocomposite possesses antibacterial property against *Escherichia coli* and *Bacillus subtilis* [52]. Reduced graphene oxide/ TiO_2 nanocomposites can also exhibit antibacterial property [53]. The antimicrobial activity of Ag–TiO_2 nanocomposites against the bacterium *Staphylococcus aureus* can be upgraded with increasing Ag content. [54]. Likewise, Chitosan-TiO_2 NPs-oleic acid nanocomposites illustrate great antimicrobial activity for both Gram-positive and Gram-negative bacteria [55]. Fabrication of cellulose acetate nanofibers embedded with TiO_2/AgNP composite NPs result in *E. coli* and *S. aureus* growth inhibition [56]. The composite films can show the most antibacterial activity against *E. coli* when 5% molar ratios of Ag/TiO_2 are added. More than 99% of *E. coli* can be stopped from growing when Ag/TiO_2/cellulose nanocomposite films are used in UV light [57]. Sonoactivated TiO_2-DVDMS nanocomposite can exhibit excellent antibacterial property in killing *S. aureus* [58]. Ag–TiO_2/Ag/a-TiO_2 nanocomposite can show antibacterial activity against *E. coli* bacteria (Fig. 1) [59].

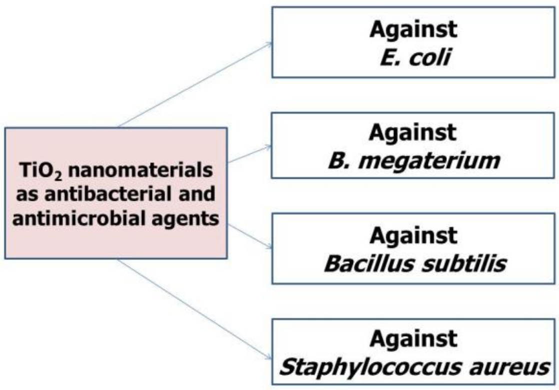

Fig. 1. TiO_2 nanomaterials as antibacterial and antimicrobial agents

4. MEDICINAL UTILIZATION

TiO_2 nanomaterials, for example, TiO_2 nanotubes (TNTs) [60], Porous titanium dioxide (TiO_2) NPs, [10] Daunorubicin-TiO_2 nanocomposites [61], TiO_2/CNT nanocomposites [62], TiO_2/PVA nanocomposite films [63], Pt/TiO_2 nanocomposite [64], Au@TiO_2

nanocomposites [65] have immense advances in medicinal industry. TNTs are employed as drug carriers to the surrounding tissues, and they have the ability to accelerate the tissue response to implant integration [60]. In pH-responsive drug delivery methods [61], nanocomposites of daunorubicin and titanium dioxide are used. TiO_2/CNT nanocomposites may be used for the detection of cancer cells and associated biorecognition when coated on carbon paper surfaces (Fig. 2) [62][63]. This is made feasible by applying a coating procedure to the nanocomposites. According to research, the stable metal–semiconductor Pt/TiO_2 nanocomposite is effective for treating cancer cells. Au@TiO_2 NCs may be employed as therapeutic agents, radiosensitizers, and photosensitizers for the treatment of cancer [65]. TiO_2 is a promising nanomaterial that is biocompatible; therefore, it is also competent for biomedical applications [66]. The nanocomposite comprised of bioactive TiO_2 particles and hydroxyapatite mixture is responsible for the expansion of bioactivity. This nanocomposite may provide improved osseointegration [67]. TiO_2/PVA nanocomposite films with high TiO_2-dopants have application in biomedical such as UV-radiation blocking to save the skin of patients during the treatment with UV-radiation [63]. TiO_2 NPs is also utilized for chemotherapeutics. There are a variety of TiO_2 nanocomposites that may be used to create biosensors. They are capable of identifying a vast array of biological compounds. GOx-entrapped TiO_2–SWCNT composite [68] may function as a glucose sensor. Arrays of Au-Doped TiO_2 Nanotubes may be used in the study of alpha-Synuclein toxicity. If Au nanorod@SiO_2 NPs are incorporated into TiO_2-chitosan hydrogel [69][70], this material may be used to detect the presence of organophosphate pesticides. These TiO_2 nanoparticles and nanocomposites have the potential to serve as glucose biosensors as well. The development of a dye sensitized TiO_2 photodetector with the potential for use as a disposable colorimetric biosensor has been accomplished. This photodetector was created for a technique of DNA detection [11].

Table 1. Application of TiO_2 in miscellaneous industries.

TiO_2 NPs	Application	References
SWCNT/TiO_2	Used as semiconductor photocatalyst in water or wastewater treatment	[15]
TiO_2–zeolite nanocomposite	useful for removing trace and untreated dye compounds by photocatalytic degradation of water pollutants	[17]
SiO_2@TiO_2 core-shell nanoparticle	Improved the degradation of phenol and methylene blue under UV irradiation by increasing the photocatalytic activity	[16]
PVA/PAA/GO-COOH@TiO_2 membranes	Showed efficient photocatalytic capacity toward the three model dyes (CR, RhB, and MB)	[24]
TiO_2 nanoparticle-coated film	Used for potential food packaging applications, especially for low density polyethylene (LDPE) film	[5]
SSPS/TiO_2 nanocomposites	showed excellent antimicrobial activity against *Staphylococcus aureus* PTCC 1431 (ATCC 25923),	[47]
(Cu_2O-TiO_2/rGO)	Used in food packaging	[48]
TiO_2 nanotubes	Act as a drug carrier to the surrounding tissues, aiming to accelerate the tissue response regarding implant integration	[50]
Daunorubicin-TiO_2 nanocomposites	Used in a “smart” pH-responsive drug delivery system	[51]
TiO_2/CNT nanocomposites	Applied in the respective biorecognition and detection of cancer cells.	[52]
TiO_2/PVA nanocomposite films	Utilized in UV-radiation blocking to save the skin of patients during the treatment with UV-radiation.	[53]
Pt/TiO_2 nanocomposite	exhibit a remarkably high photodynamic efficiency and show more effectiveness in cancer-cell treatment	[54]
TiO_2 powders	perform a better pinning to the bone	[57]
PEG-PU-TiO_2 polymer nanocomposite	shows antibacterial property against *Escherichia coli* and *Bacillus subtilis*	[52]
PBAT/TiO_2 nanocomposite	demonstrate significant antimicrobial activity against *Escherichia coli* and *Staphylococcus aureus*, to understand to the zone of inhibition	[7]
Ag/TiO_2/cellulose nanocomposite	exhibit the best antibacterial performance against *E. coli*	[57]
TiO_2/Au/MWCNT/GC	Significantly applied in biological systems	[25]
TiO_2/clay nanocomposite	Photocatalysis	[28]

The use of photoelectrodes constructed of TiO_2, 3,4-dihydroxybenzaldehyde, and Chitosan makes photoelectrochemical DNA detection possible [72]. In addition, a biosensor that is based on TiO_2 NPs has been created such that leucosis may be detected [73]. TiO_2 nanostructured films are also used in the production of biosensors of the third generation [74]. With the use of a bacterial cellulose/polypyrrole/TiO_2-Ag (BC/PPy/TiO_2-Ag) nanocomposite film, it is possible to identify and monitor the development of five potentially harmful bacteria. The electrodes that have been enhanced using TiO_2/CNT nanocomposites could, in fact, be effective in bioanalytical applications, such as the construction of whole-cell biosensors with better detection sensitivity [52].

5. SUMMARY OF THE APPLICATIONS OF TiO_2 NPS

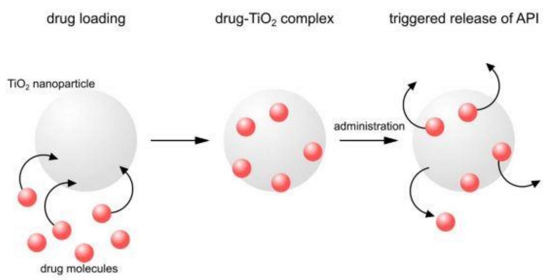

Fig. 2. Simplified mechanism of titanium (IV) oxide as drug delivery vehicle [71].

6. CONCLUSION

TiO_2 nanomaterials have vast application in various sectors. Industry use TiO_2 nanomaterials to improve their product which will be delivered to customer. These TiO_2 nanomaterials have great function against various bacteria, in degradation of organic pollutants along with air pollutants, in gas sensing, in solar cells. Some of these nanomaterials can purify both wastewater and ground water. These nanomaterials are also used in biosensor. Thus, it can be said that TiO_2 nanomaterials bring a revolution in industry.

7. REFERENCES

[1] A. Tayel, A.R. Ramadan, O.A. El Seoud, Titanium dioxide/graphene and titanium dioxide/graphene oxide nanocomposites: Synthesis, characterization and photocatalytic applications for water decontamination, Catalysts, 8 (2018) 491.
[2] K. Alamelu, B.M. Jaffar Ali, Au nanoparticles decorated sulfonated graphene-TiO2 nanocomposite for sunlight driven photocatalytic degradation of recalcitrant compound, Sol. Energy, 211 (2020) 1194–1205.
[3] H. Yang, K. Zhang, R. Shi, X. Li, X. Dong, Y. Yu, Sol-gel synthesis of TiO2 nanoparticles and photocatalytic degradation of methyl orange in aqueous TiO2 suspensions, J. Alloys Compd., 413 (2006) 302–306.
[4] X. Meng, Z. Zhang, Y. Zhang, Z. Xiao, Q. Wei, Preparation of polyacrylic acid/TiO2 nanocomposites and its application in photodegradation of methyl orange, in: Mater. Sci. Forum, Trans Tech Publications Ltd, 2011: pp. 234–238.
[5] S.H. Othman, N.R. Abd Salam, N. Zainal, R. Kadir Basha, R.A. Talib, Antimicrobial activity of TiO2 nanoparticle-coated film for potential food packaging applications, Int. J. Photoenergy, 2014 (2014).
[6] X. Wu, J. Hu, F. Wu, X. Zhang, B. Wang, Y. Yang, G. Shen, J. Liu, S. Tao, X. Wang, Application of TiO2 nanoparticles to reduce bioaccumulation of arsenic in rice seedlings (Oryza sativa L): A mechanistic study, J. Hazard. Mater., 405 (2021) 124047.
[7] R. Venkatesan, N. Rajeswari, TiO2 nanoparticles/poly(butylene adipate-co-terephthalate) bionanocomposite films for packaging applications, Polym. Adv. Technol., 28 (2017) 1699–1706.
[8] B. Kolathupalayam Shanmugam, S. Rangaraj, K. Subramani, S. Srinivasan, W.K. Aicher, R. Venkatachalam, Biomimetic TiO2-chitosan/sodium alginate blended nanocomposite scaffolds for tissue engineering applications, Mater. Sci. Eng. C, 110 (2020) 110710.
[9] T. Yanagida, Material Design of Metal Oxide Nanowires and Their Promises. In Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES), 3 (2017) 17-18.
[10] T. Wang, H. Jiang, L. Wan, Q. Zhao, T. Jiang, B.W.-A. biomaterialia, undefined 2015, Potential application of functional porous TiO2 nanoparticles in light-controlled drug release and targeted drug delivery, Elsevier,13 (2015) 354-363.
[11] I. Bernacka-Wojcik, R. Senadeera, … P.W.-B. and, undefined 2010, Inkjet printed and "doctor blade" TiO2 photodetectors for DNA biosensors, Elsevier, 25, (2010) 1229-1234.
[12] A.T. Kuvarega, B.B. Mamba, TiO2-based Photocatalysis: Toward Visible Light-Responsive Photocatalysts Through Doping and Fabrication of Carbon-Based Nanocomposites, Crit. Rev. Solid State Mater. Sci., 42 (2017) 295–346.
[13] M. Habuda-Stanic, Mirna, M. Nujic, Arsenic removal by nanoparticles: a review, Springer, 22 (2015) 8094–8123.
[14] M. Kubo, R. Moriyama, and M. Shimada, Facile fabrication of HKUST-1 nanocomposites incorporating Fe3O4 and TiO2 nanoparticles by a spray-assisted synthetic process and their dye adsorption performances, Microporous Materials, 280 (2019) 227-235.
[15] S.J. Gao, Z. Shi, W. Bin Zhang, F. Zhang, J. Jin, Photoinduced superwetting single-walled carbon nanotube/TiO2 ultrathin network films for ultrafast separation of oil-in-water emulsions, ACS Nano, 8 (2014) 6344–6352.
[16] N. Fu, X.C. Ren, J.X. Wan, Preparation of ag-coated SiO2@TiO2 core-shell nanocomposites and their photocatalytic applications towards phenol and methylene blue degradation, J. Nanomater., 2019 (2019).
[17] M.N. Chong, Z.Y. Tneu, P.E. Poh, B. Jin, R. Aryal, Synthesis, characterisation and application of TiO2-zeolite nanocomposites for the advanced treatment of industrial dye wastewater, J. Taiwan Inst. Chem. Eng., 50 (2015) 288–296.
[18] A. Ayati, A. Ahmadpour, F.F. Bamoharram, B. Tanhaei, M. Mänttäri, M. Sillanpää, A review on catalytic applications of Au/TiO2 nanoparticles in the removal of water pollutant, Chemosphere, 107 (2014) 163–174.
[19] E. Kusiak-Nejman, A.W. Morawski, TiO2/graphene-based nanocomposites for water treatment: A brief overview of charge carrier transfer, antimicrobial and photocatalytic performance, Appl.

Catal. B Environ., 253 (2019) 179–186.
[20] N. Khalfaoui-Boutoumi, H. Boutoumi, H. Khalaf, B. David, Synthesis and characterization of TiO2-Montmorillonite/Polythiophene-SDS nanocomposites: Application in the sonophotocatalytic degradation of rhodamine 6G, Appl. Clay Sci., 80–81 (2013) 56–62.
[21] P. Chen, X. Zhang, Fabrication of Pt/TiO2 Nanocomposites in alginate and their applications to the degradation of phenol and methylene blue in aqueous solutions, Clean - Soil, Air, Water, 36 (2008) 507–511.
[22] B. Szczepanik, Photocatalytic degradation of organic contaminants over clay-TiO2 nanocomposites: A review, Appl. Clay Sci., 141 (2017) 227–239.
[23] N. Krobkrong, T. Thaweechai, W. Sirisaksoontorn, Nanodot MoS_2@ 3DOM TiO_2 composites for their photocatalytic application, In Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES), 4 (2018) 2018–2028.
[24] C. Hou, T. Jiao, R. Xing, Y. Chen, J. Zhou, L. Zhang, Preparation of TiO2 nanoparticles modified electrospun nanocomposite membranes toward efficient dye degradation for wastewater treatment, J. Taiwan Inst. Chem. Eng., 78 (2017) 118–126.
[25] L.L. Qu, N. Wang, Y.Y. Li, D.D. Bao, G.H. Yang, H.T. Li, Novel titanium dioxide–graphene–activated carbon ternary nanocomposites with enhanced photocatalytic performance in rhodamine B and tetracycline hydrochloride degradation, J. Mater. Sci., 52 (2017) 8311–8320.
[26] A. Hashemi Monfared, M. Jamshidi, Synthesis of polyaniline/titanium dioxide nanocomposite (PAni/TiO2) and its application as photocatalyst in acrylic pseudo paint for benzene removal under UV/VIS lights, Prog. Org. Coatings, 136 (2019) 105257.
[27] X.N. Pham, D.T. Pham, H.S. Ngo, M.B. Nguyen, H. V. Doan, Characterization and application of C–TiO2 doped cellulose acetate nanocomposite film for removal of Reactive Red-195, Chem. Eng. Commun., 208 (2021) 304–317.
[28] A. Mishra, A. Mehta, S. Basu, Clay supported TiO2 nanoparticles for photocatalytic degradation of environmental pollutants: A review, J. Environ. Chem. Eng., 6 (2018) 6088–6107.
[29] M. Lučić, N. Milosavljević, M. Radetić, Z. Šaponjić, M. Radoičić, M.K. Krušić, The potential application of TiO2/hydrogel nanocomposite for removal of various textile azo dyes, Sep. Purif. Technol., 122 (2014) 206–216.
[30] H. Safajou, H. Khojasteh, M. Salavati-Niasari, S. Mortazavi-Derazkola, Enhanced photocatalytic degradation of dyes over graphene/Pd/TiO2 nanocomposites: TiO2 nanowires versus TiO2 nanoparticles, J. Colloid Interface Sci., 498 (2017) 423–432.
[31] E. Rommozzi, M. Zannotti, R. Giovannetti, C. Anna D'amato, S. Ferraro, M. Minicucci, R. Gunnella, A. Di Cicco, Reduced Graphene Oxide/TiO2 Nanocomposite: From Synthesis to Characterization for Efficient Visible Light Photocatalytic Applications, Mdpi.Com, 8 (2018) 598.
[32] K. Kalpana, V. Selvaraj, A novel approach for the synthesis of highly active ZnO/TiO2/Ag2O nanocomposite and its photocatalytic applications, Ceram. Int., 41 (2015) 9671–9679.
[33] Y.B. Luo, X.L. Wang, Y.Z. Wang, Effect of TiO 2 nanoparticles on the long-term hydrolytic degradation behavior of PLA, Polym. Degrad. Stab., 97 (2012) 721–728.
[34] A.M. Kamil, H.T. Mohammed, A.A. Balakit, F.H. Hussein, D.W. Bahnemann, G.A. El-Hiti, Synthesis, Characterization and Photocatalytic Activity of Carbon Nanotube/Titanium Dioxide Nanocomposites, Arab. J. Sci. Eng., 43 (2018) 199–210.
[35] N. M. Bahadur, F. Chowdhury, M. Obaidullah, M. Hossain, R. Rashid, Y. Akter, T. Furusawa, M. Sato, and N. Suzuki. "Ultrasonic-assisted synthesis, characterization, and photocatalytic application of SiO2@ TiO2 core-shell nanocomposite particles." Journal of Nanomaterials 2019 (2019).
[36] W. Wei, D. Yu, Q. Huang, Preparation of Ag/TiO2 nanocomposites with controlled crystallization and properties as a multifunctional material for SERS and photocatalytic applications, Spectrochim. Acta - Part A Mol. Biomol. Spectrosc., 243 (2020) 118793.
[37] H. Chorfi ,M. Saadoun,L. Bousselmi,B. Bessais. TiO2-ITO and TiO2-ZnO nanocomposites: Application on water treatment. InEPJ Web of Conferences, 29 (2012) 00015
[38] V. Štengl, , J. Henych, and M. Slušná. h-BN-TiO2 nanocomposite for photocatalytic applications. Journal of Nanomaterials, 2016 (2016).
[39] S. Sadrieyeh, R. Malekfar, Photocatalytic performance of plasmonic Au/Ag-TiO2 aerogel nanocomposites, J. Non. Cryst. Solids, 489 (2018) 33–39.
[40] A. Dawson, P. V. Kamat, Semiconductor-metal nanocomposites Photoinduced fusion and photocatalysis of gold-capped TiO2 (TiOa/Gold) nanoparticles, J. Phys. Chem. B, 105 (2001) 960–966.
[41] J. Mioduska, A. Zielińska-Jurek, M. Janczarek, J. Hupka, The Effect of Calcination Temperature on Structure and Photocatalytic Properties of WO3/TiO2 Nanocomposites, J. Nanomater., 2016 (2016).
[42] C. Tsai, T. Kuo, H.H.-I.J. of Photoenergy, undefined 2012, Fabrication of Al-doped TiO2 visible-light photocatalyst for low-concentration mercury removal, Hindawi.Com, 2012 (2012).
[43] F. Rashidi, R. Sarabi, Z. Ghasemi, A.S.-S. and, undefined 2010, Kinetic, equilibrium and thermodynamic studies for the removal of lead (II) and copper (II) ions from aqueous solutions by nanocrystalline TiO2, Elsevier, 48 (2010) 577-591.
[44] M. López-Muñoz, J. Aguado, … A.A.-A.C.B., undefined 2011, Mercury removal from aqueous solutions of HgCl2 by heterogeneous photocatalysis with TiO2, Elsevier, 104 (2011) 220-228.
[45] C.O. Dimkpa, J.E. McLean, D.W. Britt, A.J. Anderson, Bioactivity and biomodification of Ag, ZnO, and CuO nanoparticles with relevance to plant

performance in agriculture, Ind. Biotechnol., 8 (2012) 344–357.
[46] M.A. Muflikhun, A.Y. Chua, G.N.C. Santos, Structures, Morphological Control, and Antibacterial Performance of Ag/TiO2 Micro-Nanocomposite Materials, Adv. Mater. Sci. Eng., 2019 (2019).
[47] D. Salarbashi, T. Mohsen, S. Bibi, and B. Fazly. "Soluble soybean polysaccharide/TiO2 bionanocomposite film for food application." Carbohydrate Polymers 186 (2018) 384-393.
[48] M. Dhanasekar, V. Jenefer, R.B. Nambiar, S.G. Babu, S.P. Selvam, B. Neppolian, S.V. Bhat, Ambient light antimicrobial activity of reduced graphene oxide supported metal doped TiO2 nanoparticles and their PVA based polymer nanocomposite films, Mater. Res. Bull., 97 (2018) 238–243.
[49] R. Ahmadi, A. Tanomand, F. Kazeminava, F.S. Kamounah, A. Ayaseh, K. Ganbarov, M. Yousefi, A. Katourani, B. Yousefi, H.S. Kafil, Fabrication and characterization of a titanium dioxide (TiO2) nanoparticles reinforced bio-nanocomposite containing miswak (salvadora persica L) extract – The antimicrobial, thermo-physical and barrier properties, Int. J. Nanomedicine, 14 (2019) 3439–3454.
[50] G. Fu, P.S. Vary, C.T. Lin, Anatase TiO 2 nanocomposites for antimicrobial coatings, J. Phys. Chem. B, 109 (2005) 8889–8898.
[51] A. Alrahlah, H. Fouad, M. Hashem, A. Niazy, A.A.- Materials, Titanium Oxide (TiO2)/Polymethylmethacrylate (PMMA) Denture Base Nanocomposites: Mechanical, Viscoelastic and Antibacterial Behavior, Mdpi.Com, 11 (2018) 1096.
[52] M.S.A.S. Shah, M. Nag, T. Kalagara, S. Singh, S. V. Manorama, Silver on PEG-PU-TiO2 polymer nanocomposite films: An excellent system for antibacterial applications, Chem. Mater., 20 (2008) 2455–2460.
[53] M.S. Stan, I.C. Nica, M. Popa, M.C. Chifiriuc, O. Iordache, I. Dumitrescu, L. Diamandescu, A. Dinischiotu, Reduced graphene oxide/TiO2 nanocomposites coating of cotton fabrics with antibacterial and self-cleaning properties, J. Ind. Text., 49 (2019) 277–293.
[54] J. Prakash, P. Kumar, R. Harris, … C.S.-, Synthesis, characterization and multifunctional properties of plasmonic Ag–TiO2 nanocomposites, Iopscience.Iop.Org, 27 (2016) 355707.
[55] M.S. Hanafy, W.M. Desoky, E.M. Hussein, N.H. El-Shaer, M. Gomaa, A.A. Gamal, M.A. Esawy, O.W. Guirguis, Biological applications study of bio-nanocomposites based on chitosan/TiO2 nanoparticles polymeric films modified by oleic acid, J. Biomed. Mater. Res. - Part A, 109 (2021) 232–247.
[56] A.W. Jatoi, I.S. Kim, Q.Q. Ni, Cellulose acetate nanofibers embedded with AgNPs anchored TiO 2 nanoparticles for long term excellent antibacterial applications, Carbohydr. Polym., 207 (2019) 640–649.
[57] Y. Li, J. Tian, C. Yang, B.S. Hsiao, Nanocomposite film containing fibrous cellulose scaffold and Ag/TiO2 nanoparticles and its antibacterial activity, Polymers (Basel)., 10 (2018) 1052.
[58] Y. Wang, Y. Sun, S. Liu, L. Zhi, X. Wang, Preparation of sonoactivated TiO2-DVDMS nanocomposite for enhanced antibacterial activity, Ultrason. Sonochem., 63 (2020) 104968.
[59] O. Akhavan, Lasting antibacterial activities of Ag-TiO2/Ag/a-TiO2 nanocomposite thin film photocatalysts under solar light irradiation, J. Colloid Interface Sci., 336 (2009) 117–124.
[60] M.F. Kunrath, R. Hubler, R.S.A. Shinkai, E.R. Teixeira, Application of TiO2 Nanotubes as a Drug Delivery System for Biomedical Implants: A Critical Overview, ChemistrySelect, 3 (2018) 11180–11189.
[61] B. Chen, H. Zhang, Daunorubicin-TiO2 nanocomposites as a “smart” pH-responsive drug delivery system, Int. J. Nanomedicine, 7 (2012) 235.
[62] Q. Shen, S.K. You, S.G. Park, H. Jiang, D. Guo, B. Chen, X. Wang, Electrochemical biosensing for cancer cells based on TiO2/CNT nanocomposites modified electrodes, Electroanalysis, 20 (2008) 2526–2530.
[63] I.S. Yahia, M.I. Mohammed, A.M. Nawar, Multifunction applications of TiO 2 /poly(vinyl alcohol) nanocomposites for laser attenuation applications, Phys. B Condens. Matter, 556 (2019) 48–60.
[64] L. Liu, P. Miao, Y. Xu, Z. Tian, Z. Zou, G. Li, Study of Pt/TiO2 nanocomposite for cancer-cell treatment, J. Photochem. Photobiol. B Biol., 98 (2010) 207–210.
[65] M.C. Molina Higgins, D.M. Clifford, J. V. Rojas, Au@TiO 2 nanocomposites synthesized by X-ray radiolysis as potential radiosensitizers, Appl. Surf. Sci., 427 (2018) 702–710.
[66] M. Song, C. Pan, J. Li, R. Zhang, X. Wang, Z. Gu, Blends of TiO2 nanoparticles and poly (N-isopropylacrylamide)-co-polystyrene nanofibers as a means to promote the biorecognition of an anticancer drug, Talanta, 75 (2008) 1035–1040.
[67] L. Mohan, D. Durgalakshmi, M. Geetha, T.S.N. Sankara Narayanan, R. Asokamani, Electrophoretic deposition of nanocomposite (HAp + TiO 2) on titanium alloy for biomedical applications, Ceram. Int., 38 (2012) 3435–3443.
[68] N. Dung, D. Patil, T. Duong, H. Jung, … D.K.-S. and A.B., An amperometric glucose biosensor based on a GOx-entrapped TiO2–SWCNT composite, Elsevier, 166 (2012) 103-109.
[69] Y. An, L. Tang, X. Jiang, H. Chen, M. Yang, L. Jin, S. Zhang, C. Wang, W. Zhang, A photoelectrochemical immunosensor based on au-doped TiO2 nanotube arrays for the detection of α-synuclein, Chem. - A Eur. J., 16 (2010) 14439–14446.
[70] H. Cui, T. Zhang, Q. Lv, X. Song, … X.Z.-B. and, An acetylcholinesterase biosensor based on doping Au nanorod@ SiO2 nanoparticles into TiO2-chitosan hydrogel for detection of organophosphate pesticides, Elsevier, 141 (2019) 111452.
[71] D. Ziental, B. Czarczynska-Goslinska, D.T. Mlynarczyk, A. Glowacka-Sobotta, B. Stanisz, T. Goslinski, L. Sobotta, Titanium dioxide nanoparticles:

Prospects and applications in medicine, Nanomaterials, 10 (2020) 387.
[72] A. Victorious, A. Clifford, S. Saha, I. Zhitomirsky, L. Soleymani, Integrating TiO2 Nanoparticles within a Catecholic Polymeric Network Enhances the Photoelectrochemical Response of Biosensors, J. Phys. Chem. C, 123 (2019) 16186–16193.
[73] R. Viter, V. Smyntyna, N. Starodub, … A.T.-P., Novel immune TiO2 photoluminescence biosensors for leucosis detection, Elsevier, 47 (2012) 338-341.
[74] M. Viticoli, A. Curulli, A. Cusma, … S.K.-M.S. and…, Third-generation biosensors based on TiO2 nanostructured films, Elsevier, 26 (2006) 947-951.