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Review Article

Recent trends of titania (TiO_2) based materials: A review on synthetic approaches and potential applications

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ABSTRACT

In modern research, nanotechnology is of great interest having certain advantageous and enormous applications in various fields. Among different metal oxides, titanium dioxide (Titania) stands out among metal oxides due to its advantageous properties such as being cost-effective, non-toxic, thermally and chemically stable, biocompatible, and having a suitable band gap for solar energy conversion. It exists in three allotropic forms and can be synthesized using chemical, physical, or biological methods, with biological approaches being particularly favored for their eco-friendliness and cost-effectiveness. The multifunctional characteristics of titania enables its use in diverse industrial and research applications, including food packaging, wastewater treatment, degradation of pollutants, energy storage, and more. The review provides an overview of synthesis methods and extensive applications of titania across different life sciences and industries.

1. Introduction

Studies of nanotechnology and nano-science in modern research fields is captured more and more interest in recent decades, as these provide huge advantages and potential applications in areas like analytical testing, sensor development, extraction methods, different types of sample manipulation and industrial implementation. Nanoparticles are three-dimensional structures of less than 100 nm, with physical, chemical, and biological characteristics distinct from bulk scale materials. Categorized into carbon-containing, organic, and inorganic NPs, they form semiconductor Quantum Dots, metal sulphide, zero oxidation states, and metal oxide nanoparticles. But the MONPs are mostly synthesized and characterized (Adelantado et al., 2020). Nanotechnology involves the creation of diverse materials with various applications in scientific fields. Over the past two decades, various types of nanostructures have been fabricated, requiring specific classification. Pokropivny and Skorokhod's modified classification scheme covers all classes of nanostructures. (Lagopati, 2020).

1.1. Nanomaterials

Nanomaterials are manipulated at the nanoscale have appealing features that are more acceptable in research and capture great attention. Nanomaterials offer novel properties in various research areas, including cosmetics, health, paints, coatings, electrical equipment, water decontamination treatment, and long-lasting materials. Nanotechnology can create unique nanostructures, nano-films, nano-coatings, and nanotubes, providing enhanced features. As nanostructured materials offer novel strategies for dealing with environmental problems which enable the economical implementation of nonconventional water reservoirs in case of wastewater decontamination. As a result, nanostructure is being utilized in membrane systems, adsorption process and advanced oxidation processes (AOP) (Pasini, 2020).

Nano-size materials (NSMs) offer unique electrical, magnetic, catalytic, medical, and optical features due to quantum arrangements. Nanoparticles are fabricated using chemical, physical, hybrid, and biological methods, with biological methods being eco-friendly and safer

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(Barzinjy, 2020).

1.2. Metal oxide

Semiconductor photocatalysis has gained much public attention and proved as a promising nanotechnology in last decades for the decontaminations of dye pollutants produced from textile industries, paper pulp industry and volatile organic compounds from atmosphere. Semiconductor metal oxides (SMOs) in the form of zinc oxide (ZnO), tin oxide (SnO_2), titanium dioxide (TiO_2), nickel oxide (NiO) cuprous oxide (Cu_2O) (Wang, 2015), iron oxide (Fe_2O_3), cerium oxide (CeO_2) and tungsten oxide (WO_3), being utilized for the removal of organic pollutants. Titanium dioxide (TiO_2) is highly effective in photocatalysis due to its oxidizing potential, chemical inertness, non-toxic nature, thermal stability, affordability, corrosion resistance, and radical formation capability. (Khammar et al., 2020).

1.3. Characteristics of titania

Titania in different structural forms is excessively being used due to its exceptional sized characteristics. TiO_2-based nanostructures are being utilized for unique applications due to their unique energy band gap and quantum efficiency, highlighting their photo-physical, surface, and photo-chemical properties (Phonkhokkong, 2016).

Titanium dioxide, a semiconductor with three allotropic forms, is used in gas sensors, solar cells, photocatalysis, and antibacterial applications. Its phase transformation phenomenon makes it suitable for extreme temperature applications (Nithya, 2019). Transition metal oxides and hydroxides are being studied for efficient redox reactions in storage pathways, enhancing electrical conductance in electrode systems when combined with graphene (Fornasini, 2021). Titania, with its unique electronic band gap structure, large quantum effect, photostability, and chemical inertness, has proven effective as a photocatalyst in treating polluted water, water purification, and air purification (Nagaraj et al., 2018).

Titania, with its larger band gap and dielectric constant, is highly applicable in field effect transistors (FETs) due to its multifunctional properties in optical, chemical, and physical states. Its morphology varies based on factors like phase transition, heating temperature, and precursors (Dastan et al., 2017).

Titanium dioxide exhibits wide spectrum in ultra violet for antimicrobial activity against gram positive and gram negative bacteria, making it a selective choice for nanoparticles and photocatalytic applications (Wadhwa, 2020).

During fabrication, it has been observed when titanium dioxide is synthesized by various methods, it offers variable characteristics and activities. Many synthesis techniques for titania like micro emulsion method, pyrolysis, micro emulsion method, semi-batch or batch two stage mixed process (Catauro, 2020), chemical precipitation (Phonkhokkong, 2016), chemical vapor deposition (CVD) method, hydro thermal method, sol–gel method and solvo thermal method are used. Out of all, he sol gel method is preferred for synthesizing titania-based nanocomposites due to its ease in controlling nanoscale crystal size, structural phase, and crystallinity for photocatalysis applications (Birlik and Dagdelen, 2020).

1.4. Titania modification

TiO2 photocatalyst, despite its advantages like cost, non-toxicity, and photo-stability, has limitations like slow conversion activity, solar light limitations, and larger band gap. Modifications like metal incorporation, tungsten oxide, and metal ion doping have improved its performance. Doping noble metals with titanium dioxide can enhance photocatalytic activity by slowing electron/hole recombination and increasing energy absorption. This enhances photocatalysis by inhibiting electron/hole recombination and separating electrons and holes individually. Adsorption of titanium oxide on substrates expands adsorption capabilities, and its adsorption is crucial for pollutants degradation (Ahmed et al., 2020). Doping noble metals, transition metals, and semiconductors with appropriate electronic crystal lattices is a promising method to overcome TiO2′s drawbacks in modified nanocomposite photocatalysts (Bhange, 2016).

1.5. Applications of titania

Titania shows excellent catalytic, optical and electrical features, thus making it attractive nanomaterial in various uses like water treatment, photocatalysis, fillers (Azeez, 2018); flame resistance, ceramic uses, UV absorbance, color pigmentation and photo synthesis. By using hydrothermal approach, titania nano-particles in the colloidal form are being applied in different fields (Elbasuney, 2017). Titanium dioxide, with various morphologies, has potential applications in solar energy conversion, water purification, PEC splitting, and cosmetics. Its nanostructured fabrications can address environmental and pollution challenges and overcome energy crises (Musaev, 2020). Magnetic and photocatalytic properties have captured greater interest among researchers in various areas for enhancing photocatalytic and magnetic impacts of prepared nanocomposites (Farooq, 2021). Fig. 1 depicts the specific features of titania based materials in illustrated form.

The mechanism involves light energy generating charge carriers, causing water and oxygen molecules to react, generating hydroxyl and anionic oxygen radicals. Titania is utilized for waste degradation, self-cleaning and self-sterilization. Fig. 2 illustrates the photocatalytic scheme demonstrated by TiO_2.

2. Synthetic approaches of titania

Eco-friendly, less costly, high-productive, and toxic-free methods are preferred for nanoparticle synthesis, utilizing biomaterials for efficient fabrication and reduced time and energy consumption (Mehar, 2019). The nanoparticles of titania have been fabricated and produced on larger commercial scale during the era of 20th century. It's successful synthesis is attributed to so many uses in different fields (Lusvardi, 2017). Nanotechnology has enabled the synthesis of titanium dioxide through physical, chemical, and biological methods, which are used in daily life and characterized using sensitive instruments, biologically synthesized titanium dioxide is proceeded using;

1. Plants i.e. shrubs, herbs and trees.
2. Microorganism bacteria, algae and fungi.
3. Biological derivatives such as proteins, starches and peptides are used for the fabrication of titania nanoparticles.

Out of all methods, biological methods have been proved fruitful for the TiO_2 NPs as it is eco-friendly, non-toxic, cost effective, use less time, energy and precursors than chemical methods (Irshad, 2021).

The synthesized NPs possess more chemical activity with average diameter size of < 50 nm and relative mass concentration of nanoparticles approaches $\sim 10^{-6}$, purifying xenon from electronegative impurities as a working electrode possessing ultra-efficiency nuclear radiation detectors for new generation (Akimov, 2018).

Suspension of titanium dioxide is synthesized from the mixture of titanium tetra-isopropoxide (TTIP), sulphuric acid (H_2SO_4), ethanol, and distilled water with the help of sol–gel process. A mixture of 80 ml ethanol, 20 ml TTIP, 4 ml H_2SO_4, and distilled water was mixed, then left in an oven at 80 °C for 24 h to form white titanium dioxide crystals. Powdered form of TiO_2 was produced through grinding after heating the synthesized crystal in furnace at 400 °C (Javed, 2021) and the complete method is depicted in following Fig. 3.

For observing growth, Titania dioxide nanoparticles were biosynthesized using Curcuma longa aqueous extract for sporulation and pathogenicity of Fusarium graminearum and wheat plants using two

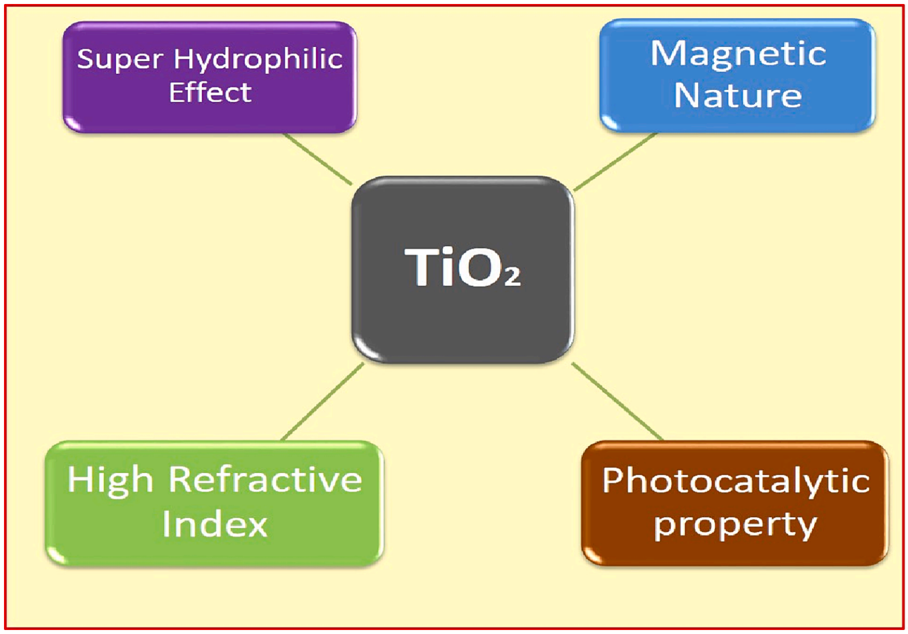

Fig. 1. Titania dioxide having specific features such as super-hydrophilic effect, magnetic, photocatalytic and high refractive index make it useful in major applications (Farooq et al., 2021).

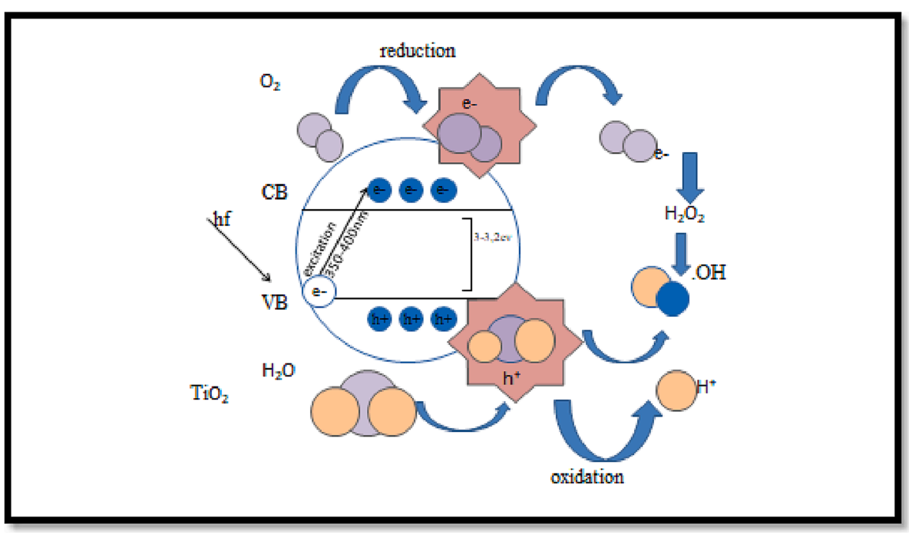

Fig. 2. Demonstration of photocatalytic scheme by TiO_2. (Chen, 2021).

methods. The fabricated NPs showed good optical and biological features (Jalill, 2016). Plant extracts have potential medical applications, and Allium eriophyllum Bios titanium nanoparticles were biologically synthesized, showing enhanced features like cytotoxicity, wound healing, anti-bacterial, anti-fungal, and anti-oxidative properties (Seydi, 2019). Fig. 4 indicates the green synthesis of TiO_2 nanoparticles being reported.

Green method biosynthesizes TiO2 nanoparticles using Sesbania grandiflora, characterized using TEM, SEM-EDX, FTIR, XRD, and UV techniques. Extracts with alkynes, alkanes, flavonoids, and secondary alcohols enhance bioavailability. The toxicity of formed nanoparticles of titania was checked by observing fish in aquatic environment as a sample as a result the titania nanoparticles were proved lethal for Zebrafish embryo (Srinivasan, 2019). Various TiO_2 based nanocomposites synthesized by adapting different methodologies and their possible applications with references are quoted in Table 1.

3. Potential applications

An important metal oxide is TiO_2 having multifunctional properties like enhanced chemical and photochemical stability, good photocatalytic activity, low cost, non-toxicity, electronic, electrical and optical properties used for different application in technology development (Khalid, 2021). Fig. 5 indicates the potential applications of TiO_2.

3.1. Food packaging

TiO_2 nanoparticles offer chemical stability, biocompatibility, antibacterial, photocatalytic activity, and UV blocking properties. A paper reports fabrication of Cs/PEO/Ag–TiO_2 nanocomposites films using solution casting method. Antimicrobial property and mechanical properties were enhanced because Ag and TiO_2 nanoparticles were embedded in Cs/PEO blend and hence used in food packaging as a natural preservative. Results revealed that by the doping of Ag/TiO_2 nanoparticles

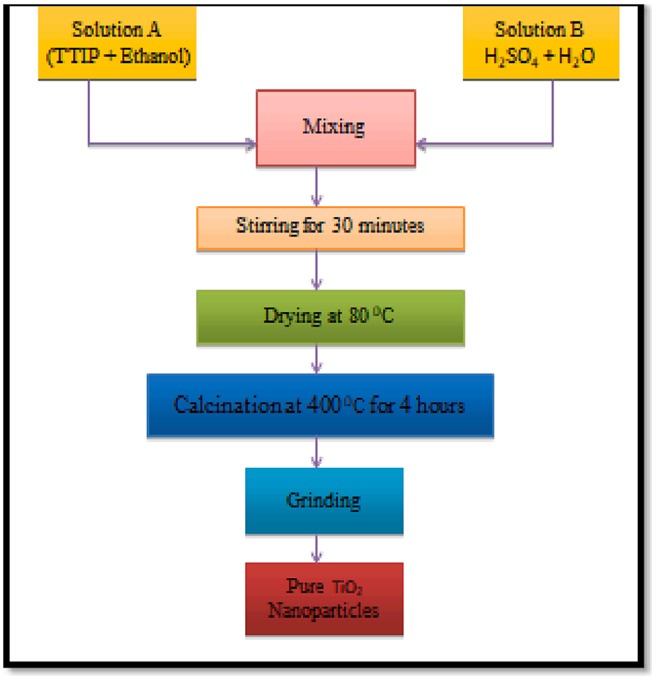

Fig. 3. Flow chart for the fabrication of titania dioxide nanoparticles (Javed, 2021).

to polymer blend, the antibacterial activity of blend was enhanced. Hence it was used in food packaging industries (Abutalib and Rajeh, 2021).

3.2. Agricultural field

Nano-sized TiO_2 is used in various fields, including pollutants removal, crop yield improvement, and agrichemicals. It affects plant biomass and physiological parameters, with its impact varying based on dose and size. A study found nano-TiO_2 reduced arsenic accumulation in rice seedlings. High nano-TiO_2 amendment reduced arsenic bio-accumulation in rice seedlings and iron plaque levels, reducing arsenic retention in the barrier and reducing roots' uptake (Wu, 2021).

3.3. Dye sensitized solar cells

Due to its favorable positions of its energy band, strong light absorption particularly in UV range, resistance against photo corrosion, better chemi-solubility and less cost, TiO_2 is generally used as a photo-anode material for dye sensitized solar cells (DSSCs). In metal oxide semiconductors, hydrogen activated modifications is of great interest because of their better photocatalytic behavior. In DSSCs, photo-anode based on H_2 treated titanium dioxide nanoparticles with the film thickness of 11.65 mm increase PCE of 6.05 % (Javed, 2021).

A study fabricated a Cu-doped TiO_2 nanoparticles/graphene composite using hydrothermal method, enhancing titanium dioxide performance. The composite was characterized using FE-SEM, TEM, and XRD. Results revealed that PCE was improved in DSSCs. Composite dye loading ability which was considerably enhanced by doping of graphene that increase JSC and PCE of cell (Dhonde et al., 2021).

Reports showed that by exposed facets of TiO_2 crystals, dye adsorption ability is highly affected. Reactivity to absorb dye molecules is enhanced by increasing the surface area of exposed facets. Solvothermally fabricated anatase TiO_2 nanoparticles were reported recently. TiO_2 nanoparticles with high IEP and surface area were fabricated using a simple solvo-thermal method, enhancing dye loading and DSC performance due to reasonable light scattering (Al-Attafi, 2021).

Due to the excellent thermal and chemical stability, appropriate band gap and low cost mostly used materials in DSSCs photo-anode is TiO_2. Due to the poor electron mobility of TiO_2, different methods such as doping, employing nano-architectures and nanocomposites have been proposed to solve the problem. A nanocomposite with optimized porosity significantly improved the performance of DSSCs, enhancing efficiency by 18.2 % compared to bare TiO_2 photo-anodes, and maintaining cell stability without disrupting current generation (Zatirostami,

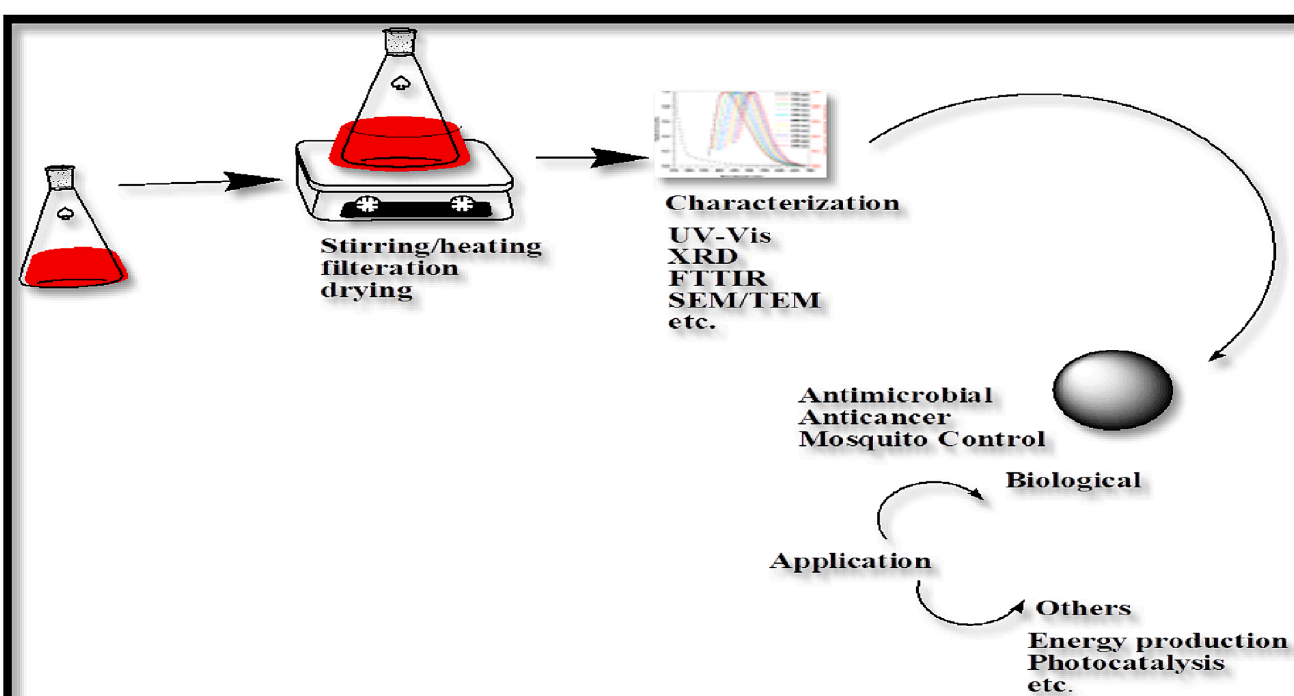

Fig. 4. Biological green route for titania synthesis (Nadeem, 2018).

Table 1
Different methodologies and applications of Titania based nanocomposites.

Composite	Method of synthesis	Applications	References
Titania-silica nanocomposite	Sol-gel method Addition method Precipitation method	Excellent photocatalytic applications	(Hendrix, 2019)
Hexagonal boron nitride (H-BN)/ titania (TiO_2)	Sol-gel method	Higher photocatalytic activities,	(Sheng, 2019)
Zn-doped TiO_2 nanoparticles	Sol gel method	Photo-degradation of methyl red under UV light.	(Aware and Jadhav, 2016)
Stearic acid/titania/ core /shell nano-capsule	Sol gel method	Thermal energy storage	(Latibari, 2015)
Titania-grafted magnetic sporopollenin	Liquid-phase deposition (LPD) method.	Tryptic digestion of rat brain cell lysate	(Hussain, 2019)
Titania/Protein Hybrid Thin films	Dip coating method	Semiconductor thin films, fabrication of crystalline Heterostructures	(Bawazer, 2018)
Titanium nanoparticles (TNPs) and titanium nanotubes (TNTs)	Hydro-thermal method	Heterogeneous Photocatalysis	(Payan et al., 2018)
Nano-titania	Green route synthesis sol–gel technique	Photocatalytic degradation of methyl orange under solar irradiation.	(Shreya, 2021)
Titanium films deposited on SiO_2 substrates	Pulsed laser ablation Methods.	Optical semiconductor	(Al-Kinany et al., 2014)
Mesoporous TiO_2–graphene nanocomposite	Green route co-doped.	photocatalytic activities	(Baeissa, 2014)

2021).

3.4. *Wastewater treatment*

Photocatalysis, primarily focusing on TiO_2, is utilized for water purification and waste water treatment, breaking down harmful organic compounds in air and water through precipitation methods. The photocatalyst Fe_2O_3–Ag_2O–TiO_2 nanoparticles, fabricated using various techniques, demonstrated excellent activity in removing flumioxazin from water samples using XRD, FTIR, FWSEM, TEM, and EDS. At acidic, basic and neutral conditions, photocatalytic studies shown that with Fe–Ag co-doped TiO_2 NPs activity was extremely enhanced by using constant duration of time. While with no Fe–Ag co-doped TiO_2 NPs addition, activity was not observed although experiments were executed for many days (Nageswara Rao, 2021).

The study reports synthesizing porous silica microspheres with immobilized titania nanoparticles for wastewater treatment using heterogeneous photocatalysis, a green and environmentally friendly method for breaking down water-soluble pollutants into harmless compounds. Results revealed that better photocatalytic activity was observed with the advantage of easily removal of photocatalyst from reaction medium (Marques, 2021).

A dark aqueous liquid known as leachate, contains a large number of heavy metals that was identified as toxic at high concentration as they can accumulate in living organisms. For the removal of various metals, TiO_2 is used. Work was reported in which by phase inversion technique, a Polyvinylidene fluoride (PVDF)-poly vinyl pyrrolidone (PVP) fiber membrane in which TiO_2 nanoparticles were incorporated with different loading concentration was synthesized for removal of copper. The fabricated fibers were characterized using SEM and EDX, revealing improved membrane porosity, flux copper adsorption and rejection, antifouling properties, and hydro-philicity with blended TiO_2 nanoparticles. For wastewater treatment, fabricated hybrid PVDF-PVP membrane incorporated with 1.0 wt% was used successfully (Abba, 2021).

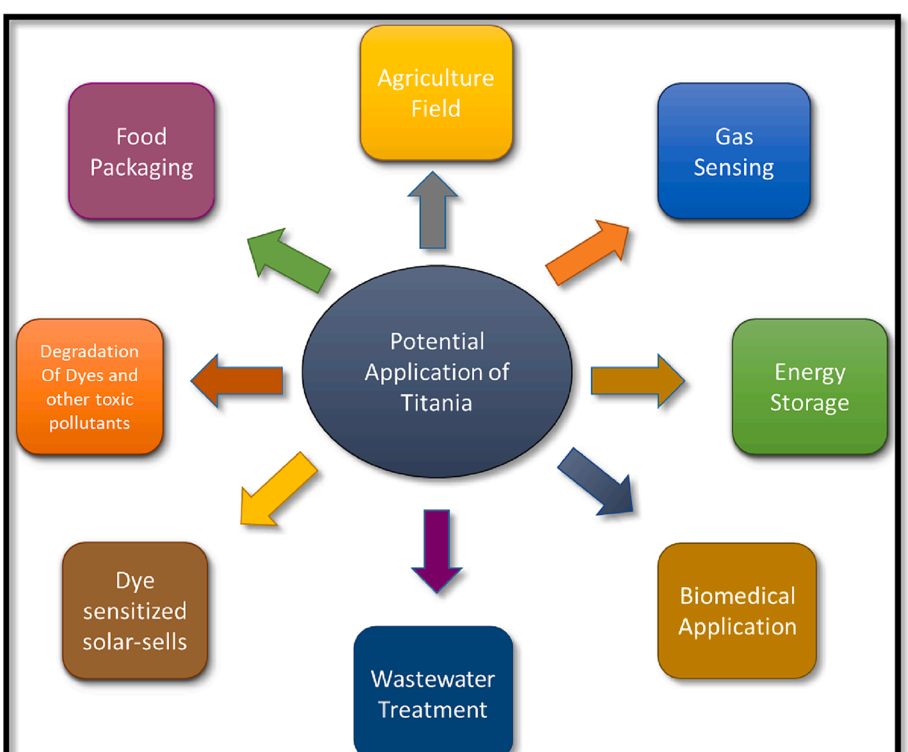

Fig. 5. Potential applications of titania (Waghmode, 2019).

3.5. Biomedical applications

On different surface coating applications, titanium dioxide is used as photocatalyst for self-disinfection and self-cleaning. Due to their anti-fogging effect, photo accelerated super hydrophobicity and specific non-toxicity, titanium dioxide has been generally used in cleaning environment. The biomedical application of titanium dioxide, synthesized using S. spinosa leaf extract, offers a stable, heat-resistant, and less harmful material, suitable for pediatric leukemia treatment, based on its cytotoxicity against Molt-4 cells (Xiaoshang, 2021).

When TiO_2 nanoparticles were incorporated in DLC films, fibroblast adhesion is improved and biofilm of gram positive and gram negative bacteria was decreased. It has self-cleaning effect due to its photocatalytic application. The study found that TiO_2 incorporation in DLC films enhanced cell viability and anti-inflammatory response, with no cytotoxic behavior observed. This highlights the potential of TiO_2 DLC as a biocompatible coating material for biomedical alloys (Wachesk, 2021).

3.6. Gas sensing

SO_2 a toxic and harmful gas, and the increasing concentration of the toxic gas SO_2, which poses environmental and health risks. Traditional SO_2 gas sensors using pristine TiO_2 nanoparticles have limitations such as high operating temperature, low response, selectivity, and stability. However, a new approach is proposed using TiO_2 nanoparticles combined with non-conducting polyvinyl formal (PVF) polymer. This PVF/TiO_2 nanocomposite sensor exhibits improved selectivity, high sensitivity at low temperatures, and fast response times compared to pristine TiO_2 sensors. Characterization techniques including FTIR, XRD, SEM, and TGA confirm the effectiveness of the PVF/TiO_2 nanocomposite. The synthesized chemi-resistive sensor based on this nanocomposite demonstrates superior performance in detecting SO_2 gas with fast response and recovery times, good selectivity, and long-term stability. Additionally, it offers advantages such as simple synthesis, cost-effectiveness, portability, low power usage, and suitability for environmental monitoring applications (Thangamani and Pasha, 2021).

Due to easy switching resistance during detection of different gas species and for the same, Titanium-based components are recommended for gas sensing due to their ability to respond to hydrogen and organic vapors. GO-TiO_2 nanocomposites have been studied for improved photocatalytic performance and gas sensor enhancement. TiO_2-loaded rGO sheets showed better sensitivity and selectivity for hydrogen and oxygen concentrations (Sagadevan, 2021).

3.7. Charge storage devices (Capacitors)

An effective way for increasing ionic conductivity and mechanical strength of solid electrolyte is the accumulation of filler ceramics into electrolytes. A composite made of titanium and potassium iodopulmbite nanocomposite solid electrolytes (NCSEs) was synthesized, characterized using SEM, FTIR, EDS, and XRD, showing high amorphous nature, increased ionic conductivity, and low activation energy (Wani, 2020).

3.8. Degradation of dyes and other toxic pollutants

In agriculture sector, 2, 4-Dichlorophenoxyacetic (2, 4-D) a toxic herbicide is used to control weeds. For photocatalytic degradation of pollutants, TiO_2 nanoparticles are mostly used because of having enhanced photocatalytic capacity, chemical stability, low cost and non-toxicity. Work was reported in which Fe doped TiO_2 nanoparticles were fabricated and used for photocatalytic degradation of 2, 4-Dichlorophenoxyacetic (2, 4-D) from water in the presence of UV and sunlight irradiation. Synthesized photocatalyst was characterized by XRD analysis and FTIR results. Results showed that in acidic and neutral pH values, maximum removal of 2, 4-Dichlorophenoxyacetic (2, 4-D) were achieved. By increasing catalyst dosage, removal efficiency was improved (Ebrahimi, 2021). A study on synthesizing TiO_2 nanoparticles on PET nanofibers showed enhanced photocatalytic activity under xenon lamp irradiation, with dye degradation up to 88 % in 10 min, demonstrating the potential of TiO_2/PET nanofibers in various applications (Yasin, 2020).

TiO_2 semiconductor is a popular photocatalyst due to its photostable, non-toxic, inexpensive, and reusable properties. It degrades chemical contaminants like dyes and microorganisms into minerals, CO_2, and H_2O. By using metal-doped titania, photo-degradation activity was enhanced then undoped or pure titania. Results revealed that 95 % and 90 % degradation of methylene blue and natural dyes was obtained by using metal doped titania (Sadia, 2021).

3.9. Thermal energy storage

The increasing demand for thermal energy necessitates the use of thermal energy storage materials with low-cost heat transfer and storage mediums, with graphene hybrid material being crucial in energy storage applications. A paper was reported in which hybrid GO/TiO_2 nanoparticles were synthesized. Hybrid nanoparticles were characterized by using FTIR, TGA, ESEM and EDX. Results revealed that heat capacity was improved in hybrid nanoparticles as compared to single type of nanoparticles. For thermal energy storage applications, hybrid nanofluid is a suitable candidate because results revealed that new TES material was developed with enhance heat capacity, thermal stability and increased specific heat (Vaka, 2020).

Paraffin is the most suitable material for thermal energy, and TiO_2 nanoparticles can enhance its thermal properties. Using FTIR, TGA, and thermal properties analyzers, results show nano TiO_2 enhances paraffin thermal conductivity without altering its chemical structure and thermal decomposition of paraffin was delayed by nano-TiO_2 particles and hence improved its thermal stability (Kumar, 2020).

The reported nanocomposites with various potential applications in different fields have been referred in Table 2.

In recent years, research on titania (TiO_2) based materials has witnessed significant advancements and diverse applications. These materials have garnered attention due to their unique properties, including photocatalytic activity, biocompatibility, and stability. Researchers have explored various synthesis methods, such as sol–gel, hydrothermal, and chemical vapor deposition, to tailor the properties of titania materials for specific applications. Additionally, novel nanostructures, including nanotubes, nanoparticles, and nanocomposites, have been developed to enhance their performance in areas such as environmental remediation, solar energy conversion, and biomedical applications. Overall, the recent research landscape reflects a growing interest in harnessing the potential of titania based materials across multidisciplinary fields.

4. Conclusions

This work explores the production and applications of titanium dioxide nanoparticles, focusing on their non-toxicity, affordability, biocompatibility, and antibacterial properties. Biological or green approaches have overcome challenges like rapid electron hole recombination and limited solar light absorption. TiO_2 nanoparticles have diverse applications in various fields, including photo anode components in solar cells, UV-blocking agents in food packaging, wastewater treatment, capacitor production, and gas sensing and thermal energy storage. Titanium-based materials show promising applications in environmental remediation, photocatalytic properties, and energy sectors, particularly in dye-sensitized solar cells and photo-electrochemical cells, for sustainable energy production. Titania's biocompatibility and antibacterial properties make it ideal for drug delivery systems, implant coatings, and antibacterial surfaces, with ongoing research advancing its

Table 2
Titania based nanocomposites with various potential applications.

Nano Composite	Synthesis Method	Potential application	References
Biosynthesized TiO_2 nanoparticles	By biosynthesis method	Effective removal of microbial pathogens and dyes present in wastewater	(Meenatchisundaram, 2021)
Activated carbon-based titania nanoparticles	By controlled hydrolysis method	Degradation of persistent wastewater pollutants	(Benjedim, 2021)
CM-B-CD functionalized Fe_3O_4@TiO_2 nanoparticles	By grafting of CM-B-CD on Fe_3O_4@TiO_2 nanoparticles	Photocatalytic degradation of polychlorinated biphenyls (PCBs) from transformer oil	(Khammar et al., 2020)
Titanium dioxide nanoparticles(TiO_2)	By sol–gel method	Wastewater treatment, desalination of drinking water and industrial water	(Abel, 2021)
PVTZ/TiO_2 nanocomposite	By in-situ solution polymerization	Possess high barrier property and good anti-corrosion performance	(Pugazhenthi and Ghouse, 2021)
TiO_2 nanoparticles	By green method	As lithium-air battery cathode.	(Pakseresht, 2021)
TiO_2 nanoparticles functionalized borneol-based polymer films	By casting method.	As a photocatalyst and bactericide	(Chen, 2021)
Chlorophyll (chl) sensitized TiO_2 nanoparticles (chl/TiO_2)	By using the incipient wetness impregnation method	Photocatalytic degradation of methylene blue (MB)	(Krishnan and Shriwastav, 2021)
Chitosan/TiO_2 bio nanocomposite CS/TiO_2Nps	By using casting method	Has great potential as wound dressing materials, promotes cell growth and gives better re-epithelization with no scar formation as well as increased antimicrobial activity	(Hanafy, 2021)
Mesoporous titania nanoparticles (MTN)	By green synthesis method	Photocatalytic degradation of crystal violet	(Mallakpour and Ramezanzade, 2021)
Polytetrafluoroethylene (PTFE-titania (TiO_2) nanocomposite films.	By supersonic spray coating technique	For application in self-cleaning, inkjet printing, antifogging windows and environmental membranes	(Kim, 2015)
Multifunctional titania nanoparticles with inherent fluorescence property.	By-one step green method	As antibacterial and cancer theranostic gents	(Masoudi, 2018)
An organic protective film on a steel surface with the help of titania nanoparticles (TNPs) combined with an organic corrosion inhibitor derived from Aganonerion polymorphum leaf extract (APLE).	TNPs were fabricated by sol–gel process. APLE was produced by Soxhlet extraction process	Improved corrosion of steel resistance	(Hoai, 2019)
Fepc-TiO_2 nanocatalsyt.	By sol–gel hydrolysis	Used to degrade toxic and harmful pollutants for environmental purification and CO_2 capture application	(Ramacharyulu, 2015)
A composite of polypyrole(PPy) and graphene nanoplatelets(GNs) decorated with TiO_2 nanoparticles (TiO_2@PPy-GNO)	By sol–gel process combined with in situ chemical polymerization	Showed enhanced NH_3 – sensing properties in the form of higher sensitivity and much faster response	(Xiang, 2015)
Titania nanoparticles	Synthesized by using liquid impregnation (LI) method	Used for safe and effective disposal of toxic heavy metals, particularly chromium	(Husnain, 2016)
Yttrium doped titania nanoparticles.	By sol–gel method	Exhibit excellent gas sensing activity	(Nithya, 2019)
Ultra-filtration clay-alumina membrane coated with a titania layer.	Via a combination of extrusion, sintering and slip casting methods	Decolorization of alizarin dye.	(Oun, 2017)
N-doped titania nanoparticles.	By plasma- assisted method	Photocatalytic self-cleaning applications	(Acayanka, 2019)
Anatase titania nanoparticles	By controlled hydrolysis method	Photodegradation of methylene blue	(Kundu and Mondal, 2019)
Nanocomposite films having paraffin and silver coated titania nanoparticles in low density polyethylene	Nanocomposite films were prepared by hot pressing	For food packaging application	(Hosseini Nasab et al., 2018)
Colored titania nanoparticles	By chemical precipitation method in the presence of glycerol	Photo-degradation of phenolic compounds	(Nawaz, 2019)

versatility and addressing societal and environmental challenges.

CRediT authorship contribution statement

Nosheen Farooq: Writing – original draft, Investigation, Conceptualization. **Parashuram Kallem:** Writing – review & editing, Funding acquisition. **Zohaib ur Rehman:** Writing – review & editing, Validation. **Muhammad Imran Khan:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Rakesh Kumar Gupta:** Writing – review & editing. **Tayaba Tahseen:** Validation, Methodology, Data curation. **Zuhra Mushtaq:** Writing – review & editing, Validation. **Norina Ejaz:** Writing – review & editing. **Abdallah Shanableh:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abba, M.U., et al., 2021. Novel PVDF-PVP hollow fiber membrane augmented with TiO2 nanoparticles: preparation, characterization and application for copper removal from leachate. Nanomaterials 11 (2), 399.
Abel, S., et al., 2021. Application of Titanium Dioxide Nanoparticles Synthesized by Sol-Gel Methods in Wastewater Treatment. J. Nanomater. 2021.
Abutalib, M., Rajeh, A., 2021. Enhanced structural, electrical, mechanical properties and antibacterial activity of Cs/PEO doped mixed nanoparticles (Ag/TiO2) for food packaging applications. Polym. Test. 93, 107013.
Acayanka, E., et al., 2019. Grafting of N-doped titania nanoparticles synthesized by the plasma-assisted method on textile surface for sunlight photocatalytic self-cleaning applications. Surf. Interfaces 17, 100361.
Adelantado, C., Ríos, Á., Zougagh, M., 2020. A new nanometrological strategy for titanium dioxide nanoparticles screening and confirmation in personal care products by CE-spICP-MS. Talanta 219, 121385.

Ahmed, D.S., Mohammed, M.K., Mohammad, M.R., 2020. Sol–gel synthesis of Ag-doped titania-coated carbon nanotubes and study their biomedical applications. Chem. Pap. 74 (1), 197–208.

Akimov, D.Y., et al., 2018. Synthesis of Titanium Nanoparticles in Liquid Xenon by a High-Voltage Discharge. Tech. Phys. Lett. 44 (7), 637–639.

Al-Attafi, K., et al., 2021. Solvothermally synthesized anatase TiO2 nanoparticles for photoanodes in dye-sensitized solar cells. Sci. Technol. Adv. Mater. 22 (1), 100–112.

Al-Kinany, M., Al-Dahash, G.A., Al-Shahban, J., 2014. Experimental Study of a Synthesis Ti Nanoparticles with Nanosecond Laser Pulses. Aust. J. Basic Appl. Sci. 8 (10), 283–289.

Aware, D.V., Jadhav, S.S., 2016. Synthesis, characterization and photocatalytic applications of Zn-doped TiO 2 nanoparticles by sol–gel method. Appl. Nanosci. 6 (7), 965–972.

Azeez, F., et al., 2018. The effect of surface charge on photocatalytic degradation of methylene blue dye using chargeable titania nanoparticles. Sci. Rep. 8 (1), 1–9.

Baeissa, E., 2014. Green synthesis of methanol by photocatalytic reduction of CO2 under visible light using a graphene and tourmaline co-doped titania nanocomposites. Ceram. Int. 40 (8), 12431–12438.

Barzinjy, A.A., et al., 2020. Green and eco-friendly synthesis of Nickel oxide nanoparticles and its photocatalytic activity for methyl orange degradation. J. Mater. Sci. Mater. Electron. 31, 11303–11316.

Bawazer, L., et al., 2018. Enzymatically-controlled biomimetic synthesis of titania/protein hybrid thin films. J. Mater. Chem. B 6 (23), 3979–3988.

Benjedim, S., et al., 2021. Activated carbon-based coloured titania nanoparticles with high visible radiation absorption and excellent photoactivity in the degradation of emerging drugs of wastewater. Carbon 178, 753–766.

Bhange, P., et al., 2016. Photocatalytic degradation of methylene blue on Sn-doped titania nanoparticles synthesized by solution combustion route. Mater. Res. Bull. 76, 264–272.

Birlik, I., Dagdelen, D., 2020. Synergistic effect of manganese and nitrogen codoping on photocatalytic properties of titania nanoparticles. Bull. Mater. Sci. 43 (1), 1–8.

Catauro, M., et al., 2020. Thermal, chemical and antimicrobial characterization of bioactive titania synthesized by sol–gel method. J. Therm. Anal. Calorim. 142 (5), 1767–1774.

Chen, X., et al., 2021. TiO2 nanoparticles functionalized borneol-based polymer films with enhanced photocatalytic and antibacterial performances. Environ. Technol. Innov. 21, 101304.

Dastan, D., Chaure, N., Kartha, M., 2017. Surfactants assisted solvothermal derived titania nanoparticles: synthesis and simulation. J. Mater. Sci. Mater. Electron. 28 (11), 7784–7796.

Dhonde, M., Sahu, K., Murty, V., 2021. Cu-doped TiO2 nanoparticles/graphene composites for efficient dye-sensitized solar cells. Sol. Energy 220, 418–424.

Ebrahimi, R., et al., 2021. Synthesis and application of Fe-Doped TiO2 nanoparticles for photodegradation of 2, 4-D from aqueous solution. Arab. J. Sci. Eng. 46 (7), 6409–6422.

Elbasuney, S., 2017. Sustainable steric stabilization of colloidal titania nanoparticles. Appl. Surf. Sci. 409, 438–447.

Farooq, N., et al., 2021. Au@ GO@ g-C3N4 and Fe2O3 nanocomposite for efficient photocatalytic and electrochemical applications. Surf. Interfaces 26, 101399.

Farooq, T., Surana, K., Mukherjee, S., 2021. Synthesis of titanium dioxide TiO2 thin film to achieve resistive switching property for the application of nonvolatile memory. Mater. Today:. Proc. 34, 616–620.

Fornasini, L., et al., 2021. In situ decoration of laser-scribed graphene with TiO2 nanoparticles for scalable high-performance micro-supercapacitors. Carbon 176, 296–306.

Hanafy, M.S., et al., 2021. Biological applications study of bio-nanocomposites based on chitosan/TiO2 nanoparticles polymeric films modified by oleic acid. J. Biomed. Mater. Res. A 109 (2), 232–247.

Hendrix, Y., et al., 2019. Influence of synthesis conditions on the properties of photocatalytic titania-silica composites. J. Photochem. Photobiol. A Chem. 371, 25–32.

Hoai Vu, N.S., et al., 2019. Improved corrosion resistance of steel in ethanol fuel blend by titania nanoparticles and Aganonerion polymorphum leaf extract. ACS Omega 4 (1), 146–158.

Hosseini Nasab, N., Jalili, M.M., Farrokhpay, S., 2018. Application of paraffin and silver coated titania nanoparticles in polyethylene nanocomposite food packaging films. J. Appl. Polym. Sci. 135 (8), 45913.

Husnain, A., et al., 2016. Immobilization in cement mortar of chromium removed from water using titania nanoparticles. J. Environ. Manage. 172, 10–17.

Hussain, D., et al., 2019. Facile liquid-phase deposition synthesis of titania-coated magnetic sporopollenin for the selective capture of phosphopeptides. Anal. Bioanal. Chem. 411 (15), 3373–3382.

Irshad, M.A., et al., 2021. Synthesis, characterization and advanced sustainable applications of titanium dioxide nanoparticles: A review. Ecotoxicol. Environ. Saf. 212, 111978.

Jalill, A., et al., 2016. Biological synthesis of Titanium Dioxide nanoparticles by Curcuma longa plant extract and study its biological properties. World Scientific News 49 (2), 204–222.

Javed, H.M.A., et al., 2021. Hydrogen treated TiO2 nanoparticles onto FTO glass as photoanode for dye-sensitized solar cells with remarkably enhanced performance. Int. J. Hydrogen Energy 46 (27), 14311–14321.

Khalid, A., et al., 2021. A practical method for incorporation of Fe (III) in Titania matrix for photocatalytic applications. Mater. Res. Express 8 (4), 045006.

Khammar, S., Bahramifar, N., Younesi, H., 2020. Preparation and surface engineering of CM-β-CD functionalized Fe3O4@ TiO2 nanoparticles for photocatalytic degradation of polychlorinated biphenyls (PCBs) from transformer oil. J. Hazard. Mater. 394, 122422.

Kim, D.-Y., et al., 2015. Self-cleaning superhydrophobic films by supersonic-spraying polytetrafluoroethylene–titania nanoparticles. J. Mater. Chem. A 3 (7), 3975–3983.

Krishnan, S., Shriwastav, A., 2021. Application of TiO2 nanoparticles sensitized with natural chlorophyll pigments as catalyst for visible light photocatalytic degradation of methylene blue. J. Environ. Chem. Eng. 9 (1), 104699.

Kumar, P.M., et al., 2020. Experimental study on thermal properties of nano-TiO2 embedded paraffin (NEP) for thermal energy storage applications. Mater. Today:. Proc. 22, 2153–2159.

Kundu, A., Mondal, A., 2019. Photodegradation of methylene blue under direct sunbeams by synthesized anatase titania nanoparticles. SN Applied Sciences 1 (3), 1–17.

Lagopati, N., et al., 2020. Nanomedicine: Photo-activated nanostructured titanium dioxide, as a promising anticancer agent. Pharmacol. Ther., 107795

Latibari, S.T., et al., 2015. Facile synthesis and thermal performances of stearic acid/titania core/shell nanocapsules by sol–gel method. Energy 85, 635–644.

Lusvardi, G., et al., 2017. Synthesis and characterization of TiO2 nanoparticles for the reduction of water pollutants. Materials 10 (10), 1208.

Mallakpour, S., Ramezanzade, V., 2021. Tragacanth gum mediated green fabrication of mesoporous titania nanomaterials: Application in photocatalytic degradation of crystal violet. J. Environ. Manage. 291, 112680.

Marques, A.C., et al., 2021. Porous Silica Microspheres with Immobilized Titania Nanoparticles for In-Flow Solar-Driven Purification of Wastewater. Global Chall. 5 (5), 2000116.

Masoudi, M., et al., 2018. Multifunctional fluorescent titania nanoparticles: green preparation and applications as antibacterial and cancer theranostic agents. Artif. Cells Nanomed. Biotechnol. 46 (sup2), 248–259.

Meenatchisundaram, N., et al., 2021. Biosynthesized TiO2 nanoparticles an efficient biogenic material for photocatalytic and antibacterial applications. Energy Environ. p. 0958305X211000261.

Mehar, S., et al., 2019. Green Synthesis of Zinc oxide Nanoparticles from Peganum harmala, and its biological potential against bacteria. Front. Nanosci. Nanotech 6, 1–5.

Musaev, K., 2020. Sol-gel synthesis and characterization of nickel doped titania nanoparticles. Sci. & Educ. 1 (9).

Nadeem, M., et al., 2018. The current trends in the green syntheses of titanium oxide nanoparticles and their applications. Green Chem. Lett. Rev. 11 (4), 492–502.

Nagaraj, G., Raj, A.D., Irudayaraj, A.A., 2018. Next generation of pure titania nanoparticles for enhanced solar-light photocatalytic activity. J. Mater. Sci. Mater. Electron. 29 (5), 4373–4381.

Nageswara Rao, T., et al., 2021. Photocatalytic Applications of Fe–Ag Co-Doped TiO2 Nanoparticles in Removal of Flumioxazin Pesticide Residues in Water. Frontiers in Nanotechnology 3, 14.

Nawaz, R., et al., 2019. Glycerol-mediated facile synthesis of colored titania nanoparticles for visible light photodegradation of phenolic compounds. Nanomaterials 9 (11), 1586.

Nithya, N., et al., 2019. Synthesis and characterization of yttrium doped titania nanoparticles for gas sensing activity. Mater. Sci. Semicond. Process. 99, 14–22.

Oun, A., et al., 2017. Tubular ultrafiltration ceramic membrane based on titania nanoparticles immobilized on macroporous clay-alumina support: elaboration, characterization and application to dye removal. Sep. Purif. Technol. 188, 126–133.

Pakseresht, S., et al., 2021. Biologically synthesized TiO2 nanoparticles and their application as lithium-air battery cathodes. Ceram. Int. 47 (3), 3994–4005.

Pasini, S.M., et al., 2020. *An overview on nanostructured TiO2–containing fibers for photocatalytic degradation of organic pollutants in wastewater treatment.* Journal of Water. Process. Eng., 101827

Payan, A., Fattahi, M., Roozbehani, B., 2018. Synthesis, characterization and evaluations of TiO 2 nanostructures prepared from different titania precursors for photocatalytic degradation of 4-chlorophenol in aqueous solution. J. Environ. Health Sci. Eng. 16 (1), 41–54.

Phonkhokkong, T., et al., 2016. synthesis and characterization of tio2 nanopowders for fabrication of dye sensitized solar cells. Dig. J. Nanomater. Biostruct. 11 (1), 81–90.

Pugazhenthi, I., Ghouse, S.M., 2021. Corrosion protection performance of titania nanoparticles filled poly (4-methyl-5-vinylthiazole) applied on mild steel in 3.5% sodium chloride solution. J. Plast. Film Sheeting 37 (1), 17–32.

Ramacharyulu, P., et al., 2015. Iron phthalocyanine modified mesoporous titania nanoparticles for photocatalytic activity and CO 2 capture applications. PCCP 17 (39), 26456–26462.

Sadia, M., et al., 2021. Metal doped titania nanoparticles as efficient photocatalyst for dyes degradation. Journal of King Saud University-Science 33 (2), 101312.

Sagadevan, S., et al., 2021. Enhanced gas sensing and photocatalytic activity of reduced graphene oxide loaded TiO2 nanoparticles. Chem. Phys. Lett. 780, 138897.

Seydi, N., et al., 2019. Synthesis of titanium nanoparticles using Allium eriophyllum Boiss aqueous extract by green synthesis method and evaluation of their remedial properties. Appl. Organomet. Chem. 33 (11), e5191.

Sheng, Y., et al., 2019. Sol-gel synthesized hexagonal boron nitride/titania nanocomposites with enhanced photocatalytic activity. Appl. Surf. Sci. 465, 154–163.

Shreya, M., et al., 2021. Facile green route sol–gel synthesis of nano-titania using bio-waste materials as templates. Clean Techn. Environ. Policy 23 (1), 163–171.

Srinivasan, M., et al., 2019. Green synthesis and characterization of titanium dioxide nanoparticles (TiO2 NPs) using Sesbania grandiflora and evaluation of toxicity in zebrafish embryos. Process Biochem. 80, 197–202.

Thangamani, G., Pasha, S.K., 2021. Titanium dioxide (TiO2) nanoparticles reinforced polyvinyl formal (PVF) nanocomposites as chemiresistive gas sensor for sulfur dioxide (SO2) monitoring. Chemosphere 275, 129960.
Vaka, M., et al., 2020. Synthesis of hybrid graphene/TiO2 nanoparticles based high-temperature quinary salt mixture for energy storage application. J. Storage Mater. 31, 101540.
Wachesk, C., et al., 2021. In vivo biocompatibility of diamond-like carbon films containing TiO2 nanoparticles for biomedical applications. J. Mater. Sci. - Mater. Med. 32 (9), 1–10.
Wadhwa, S., et al., 2020. Titania-based porous nanocomposites for potential environmental applications. Bull. Mater. Sci. 43 (1), 1–9.
Waghmode, M.S., et al., 2019. Studies on the titanium dioxide nanoparticles: Biosynthesis, applications and remediation. SN Applied Sciences 1 (4), 1–9.
Wang, B., et al., 2015. Synthesis, characterization and activity of an immobilized photocatalyst: natural porous diatomite supported titania nanoparticles. J. Colloid Interface Sci. 438, 204–211.
Wani, S.I., 2020. Synthesis, properties and application of titania incorporated potassium iodoplumbite nanocomposite solid electrolyte for the manufacture of high value capacitors. Electrochimica Acta 342, 136097.
Wu, X., et al., 2021. Application of TiO2 nanoparticles to reduce bioaccumulation of arsenic in rice seedlings (Oryza sativa L.): A mechanistic study. J. Hazard. Mater. 405, 124047.
Xiang, C., et al., 2015. Ammonia sensor based on polypyrrole–graphene nanocomposite decorated with titania nanoparticles. Ceram. Int. 41 (5), 6432–6438.
Xiaoshang, G., et al., 2021. Biosynthesized TiO2 nanoparticles and their applications for the treatment of pediatric acute leukemia. Mater. Res. Express 8 (1), 015022.
Yasin, S.A., et al., 2020. Methylene blue photocatalytic degradation by TiO2 nanoparticles supported on PET nanofibres. Mater. Today:. Proc. 20, 482–487.
Zatirostami, A., 2021. Fabrication of dye-sensitized solar cells based on the composite TiO2 nanoparticles/ZnO nanorods: Investigating the role of photoanode porosity. Mater. Today Commun. 26, 102033.