



HAL
open science

Nanostructured Titanium Dioxide (NS-TiO₂)

Bochra Bejaoui, Imen Bouchmila, Khaoula Nefzi, Imen Belhadj Slimen, Sidrine Koumbad, Patrick Martin, Nicolas Joly, Naceur M'Hamdi

► **To cite this version:**

Bochra Bejaoui, Imen Bouchmila, Khaoula Nefzi, Imen Belhadj Slimen, Sidrine Koumbad, et al.. Nanostructured Titanium Dioxide (NS-TiO₂). IntechOpen, 2023, <10.5772/intechopen.111648>. <hal-04130001>

HAL Id: hal-04130001

<https://hal.science/hal-04130001v1>

Submitted on 30 May 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

7,000

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Chapter

Nanostructured Titanium Dioxide (NS-TiO₂)

*Bochra Bejaoui, Imen Bouchmila, Khaoula Nefzi,
Imen Belhadj Slimen, Sidrine Koumbad, Patrick Martin,
Nicolas Joly and Naceur M'Hamdi*

Abstract

During the past decade, research in the area of synthesis and applications of nanostructured titanium dioxide (NS TiO₂) has become tremendous. NS TiO₂ materials have shown great potential and a wide range of applications. The decrease in the particle size and the increase of the surface/volume ratio lead to the increase of the specific surface and the modification of the physicochemical properties and the appearance of new interesting properties (photocatalytic, optical, magnetic, electronic...). Their new morphology even allows the appearance of new biological properties. NS TiO₂ can thus be used for the same applications as those known for their precursors before transformation and their nanostructures are accompanied by new properties allowing applications. This chapter briefly describes the synthesis process of the different NS TiO₂, their chemical and surface modifications, and their application. The preparation of NS TiO₂, including nanoparticles, nanorods, nanowires, nanosheets, nanofibers, and nanotubes is described. This chapter discusses the effects of precursor properties and synthesis conditions on the structure, crystallinity, surface specificity, and morphology of titanium dioxide nanoparticles. Recent advances in NS TiO₂ in nano-biosensing, medical implants, drug delivery, and antibacterial fields, pharmaceutical applications, as well as their toxicity and biocompatibility, were presented.

Keywords: titanium dioxide nanoparticle, syntheses process, chemical methods, physical methods, biosynthesis, environmental applications, biomedical applications, biocompatibility

1. Introduction

Nanotechnology encompasses biology, chemistry, materials science, medicine and physics. Today, With the advent of nanoscience and titanium dioxide nanostructured materials nanotechnology, nanostructured materials are an important research area due to their various unique properties. Among all transition metal oxides, TiO₂ nanostructures are the most attractive materials in modern science and technology [1]. TiO₂ is used commercially in donuts, cosmetics, pigments [2], catalysts, sunscreens [3, 4], solar cells [5], water splitting, and more. TiO₂ is used in plastics, paints, varnishes, paper, pharmaceuticals, inks, pharmaceuticals, toothpaste, food, and

industry [6, 7]. Nanostructured titanium dioxide (NS-TiO₂) is a non-toxic, environmentally friendly, inexpensive, and efficient functional material with a broad range of applications [8–11]. In the past decade, nanostructured TiO₂, which can have either a stoichiometric or nonstoichiometric composition, has attracted increasing attention from researchers around the world as a promising highly efficient photocatalyst for the synthesis of organic compounds that meets the principles of green chemistry [12–17]. Today, nano-structured materials are an important area of research due to their several unique characteristic features. Among all the transition metal oxides, TiO₂ nanostructures are the best-looking materials in modern science and technology [1]. Nano-TiO₂ nanostructures include titanium dioxide nanoparticles (TiO₂-NPs) and titanium dioxide nanotubes (TNTs) [18]. With the advent of nanotechnology, NS-TiO₂ has found many applications. Nanoscale titanium dioxide (nano-TiO₂) has been widely used in environmental protection, cosmetics, antibacterial agents, self-cleaning coatings and cancer treatment, solar cells, photocatalysis, and composite nanofillers [19–21]; due to the fact of its unique size and high specific surface area, nano-TiO₂ has more stable physical and chemical properties compared to titanium dioxide. In addition, nano-TiO₂ has great application potential in biomedical fields [22, 23] due to the fact of its good antibacterial activity, favorable biocompatibility, and unique photocatalytic activity [24]. Research has shown that nanostructured TiO₂ elicits a favorable molecular response and osseointegration, with better bone formation than non-nanostructured materials [25–27]. The unique physicochemical properties of all these forms of NS-TiO₂, render this material a promising future in many applications. Several reviews and reports on different aspects of titanium dioxide, including its properties, preparation, modification, and application, have been published. However, despite advances in the development of nanostructured TiO₂ systems for bone repair, review articles addressing this topic are still scanty [28].

The purpose of this chapter is to introduce and discuss the properties [29], fabrication, modification, and applications of nanostructured titanium dioxide (NS-TiO₂). With the advent of nanotechnology, NS-TiO₂ has found many applications.

2. Synthesis process of NS TiO₂

Various synthesis methods such as sol-gel, hydrothermal and solvothermal methods, vapor deposition, electrochemical deposition, oxidation, and sonochemical and micro-waves methods are used to obtain high-quality TiO₂ nanostructures [12, 15]. In this section, we will analyze the most used methods for the preparation of TiO₂ nanostructures.

2.1 Chemical and physical methods

2.1.1 Sol: gel process

Sol-gel is a versatile method used for the synthesis of TiO₂ nanostructures of different morphologies such as sheets, tubes, particles, wires, rods, mesoporous, and aerogels [30–32]. Mehrotra and Singh [33] suggested different steps and conditions that can control the morphology of the final products in the sol-gel process (**Figure 1**).

The sol-gel method can use two ways of synthesis: the inorganic or colloidal route in which the precursors used are metal salts such as chlorides, nitrates, and oxychlorides in an aqueous solution. The Metallo-organic or polymeric route: obtained from metal

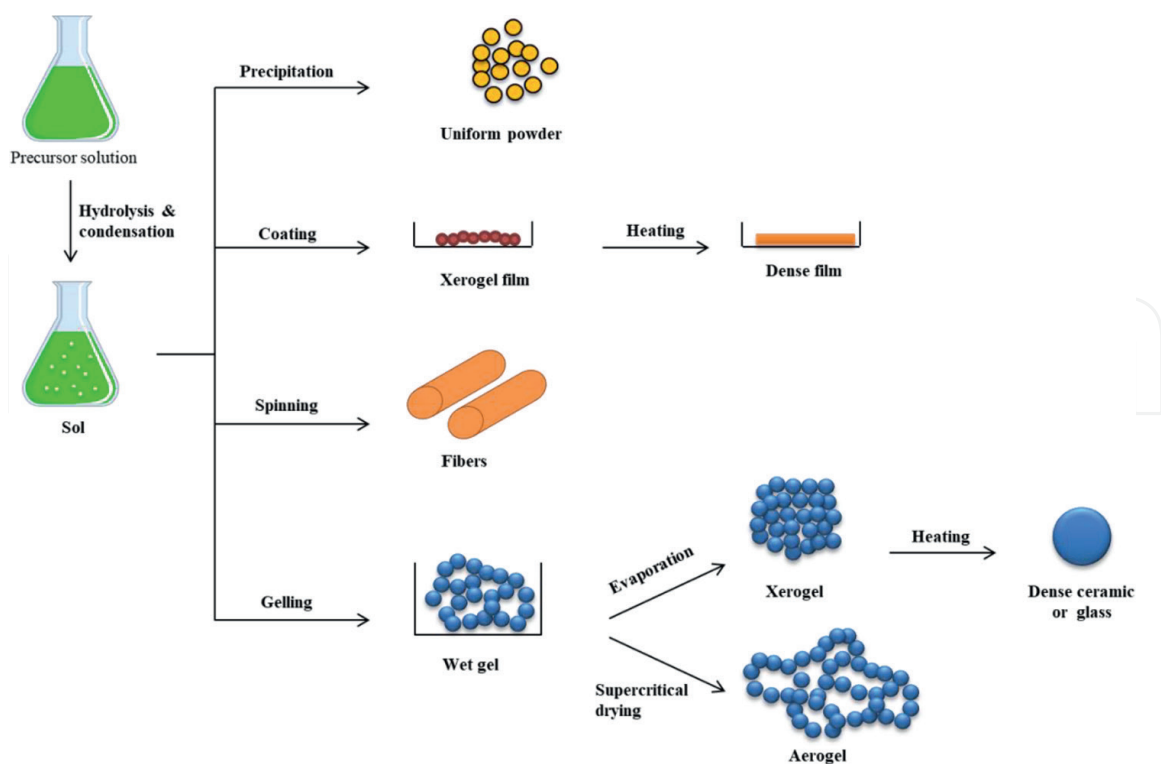


Figure 1.
Sol-gel process steps for the synthesis of TiO₂ nanostructures [30, 32, 33].

alkoxides in organic solutions. The polymerization reaction to obtain titanium dioxide takes place in two steps, namely hydrolysis, and condensation.

2.1.2 Hydrothermal and solvothermal processing

These two methods of synthesis are quite similar. The hydrothermal method is considered one of the most promising techniques for obtaining nanostructured TiO₂ at stable temperatures and pressures. It has the advantage of following simple steps and being inexpensive. The hydrothermal technique allows the production of high-quality 1D nanostructures, especially nanorods. By adapting the synthesis parameters, it is possible to control the morphology of the structures. However, the disadvantages of this method include the high capital requirement for instrumentation, the inability to monitor crystal growth, and the method can only be performed under supercritical solvent conditions [32, 34, 35]. Solvothermal methods use non-aqueous solvents with very high boiling points. When synthesizing with the solvents, better control of the properties of the titanium dioxide particles is achieved. The physicochemical characteristics (viscosity, polarity, boiling point, thermal conductivity, dielectric constant) of the solvent have a great influence on the nanostructures of the product [36]. Kathirvel et al. [37] prepared TiO₂ nanocrystals by the solvothermal method using six alcohols of different classes (primary, secondary, and tertiary). The synthesis was carried out using titanium isopropoxide as a precursor at a temperature of 150°C for 8 h. The crystallinity and morphology of TiO₂ nanocrystals varied depending on the chain length and the class of alcohol [37]. Li et al. [38] on the other hand, used the solvothermal method to obtain TiO₂ microspheres with suitable size without surfactant in a single step. The synthesis was performed using titanocene dichloride and acetone, heated at 180°C for 12 h [39]. It has been shown that the addition of surfactants to the synthesis effectively controls the growth of the particles [40–42].

2.1.3 Vapor deposition

Deposition methods form high-quality solid materials by condensing materials in a vaporous state. The deposition process is usually performed at low pressure in a vacuum chamber. If a chemical reaction occurs, it is called chemical vapor deposition (CVD) and if no reaction occurs, it is called physical vapor deposition (PVD). In this process, a precursor (solid or liquid) is heated to form an active gaseous reactant that is transferred to the reaction chamber. When the substrate is exposed to the volatile precursor, a reaction occurs on the surface of the substrate and the deposition process begins to produce the desired product. The precursors used in this method are highly volatile, non-toxic, and pyrophoric. The by-products formed during this process are degraded through the reaction chamber by the gas flow. This technique proved to be suitable to prepare TiO₂ nanostructures with tailored morphologies [43, 44].

2.1.4 Oxidation method

The principle of this method is to oxidize metallic titanium into titanium oxide by anodization or by the use of oxidants. Anodization or anodic oxidation consists in performing a surface treatment to form a titanium structure of pores/nanotubes on TiO₂. Oxidation of titanium can be achieved by using oxygen sources such as hydrogen peroxide, pure oxygen, acetone, and a mixture of argon and oxygen [30]. Mohan et al. [45] used this technique to synthesize self-organized titanium oxide nanotube layers from titanium alloys in electrolyte mixtures. The length and diameter of the nanotubes were controlled by playing on different anodization parameters such as temperature and time. Significant results were observed at 25°C. Indeed, at this temperature compared to others, smooth and circular nanotube arrays, with no apparent defects in their morphology were obtained [45]. From a previously treated titanium plate dissolved in 30% hydrogen peroxide, titanium dioxide nanorods were obtained by a dissolution precipitation mechanism. The addition of inorganic sodium salts can lead to the formation of anatase (NaF and Na₂SO₄) or rutile (NaCl addition) titanium dioxide nanorods [46].

2.1.5 Electrochemical anodization/electrodeposition process

Electrochemical anodization is an electrochemical process used to manufacture nanoparticles such as titanium nanotubes and nanopores. This method consists in growing the oxide layer on the metal surface. This process is performed in a standard two-electrode system immersed in a first, second, or third-generation electrolyte solution. The titanium forms the anode electrode and the platinum the cathode.

2.1.6 Sonochemical synthesis

Sonochemical synthesis has proven to be an efficient method to obtain nanoparticles with interesting properties in a short time [47]. The chemical effects observed during this technique are attributed to acoustic cavitation phenomena. Indeed, during cavitation in a liquid medium, there is formation, growth, and collapse of bubbles in the liquid. The violent implosion of the bubbles in less than a microsecond generates short-lived hot spots with a temperature of about 5000 K, pressures close to 1000 atm, and cooling rates higher than 10⁹ K/s. Under these conditions, metal ions are reduced to metal or metal oxide nanoparticles [48]. The main advantage of this

method is that the reaction times are reduced and the manipulations are performed under ambient conditions. In addition, it is a simple technique to implement and energy efficient. The nanostructures obtained are ultrafine particles. Studies have shown that ultrasonic synthesis of TiO₂ nanostructures can improve their properties. This technique is more efficient than other methods including microwaves [49].

2.1.7 Microwave method

The microwave-assisted synthesis method also uses electromagnetic waves such as sonication. Titanium dioxide can be synthesized by this technique at frequencies ranging from 0.3 to 300 GHz and wavelengths from 0.001 to 1 m. Two different mechanisms can be involved in microwave charring: dipolar polarization and ionic conduction [50]. Any material or substance containing mobile electric charges such as polar molecules or conducting ions can be heated using microwaves. In the dipolar polarization mechanism, microwave energy allows molecules to try to orient themselves with the electric field oscillating billions of times per second. The constant rotary motion of the molecule trying to align itself with the field causes friction and collisions.

3. Physical and chemical properties of NS TiO₂

Titanium dioxide is one of the most studied and well-researched compounds in materials science, due to its outstanding and exceptional properties which include stability of its chemical structure, biocompatibility, physical, optical, and electrical properties, nontoxicity, corrosion resistance, and low cost [51–53]. Generally, the morphology and physical/chemical properties of TiO₂ nanostructures depend on the synthesis process, precursor type, and concentration, use of capping agents, synthesis temperature, pressure, and time [31]. Titanium dioxide, CI 77891, also known as Titanium (IV) oxide or Titania, CAS No: 13463-67-7 is a naturally occurring oxide with the chemical formula TiO₂ and a molecular weight of 79.87 g mol⁻¹. It belongs to the family of transition metal oxides [54]. The most important titanium minerals are rutile (TiO₂), ilmenite (FeTiO₃), and titanite (CaTiSiO₅) [54]. In nature, titanium dioxide occurs mainly in three crystalline forms: rutile, anatase, and brookite. In addition, other polymorphs have also been reported (**Figure 2**) [32]. In addition, there are at least 3 reported non-crystalline TiO₂ phases: a low-density amorphous TiO₂ and two high-density amorphous TiO₂ types. TiO₂ (II) and TiO₂ (H) are high-pressure forms that have been synthesized from the rutile phase [31, 54–56].

In various technologically relevant applications, nano-size-scaled materials have shown beneficial properties related not only to their chemical composition but also to the small dimensions and the large surface-to-volume ratio. Generally, a material is defined as a nanomaterial when it has a specific surface area by volume greater than 60 m²cm⁻³, excluding materials consisting of particles with a size lower than 1 nm [57].

The high surface area brought about by small particle size is a crucial parameter for the high performance of many TiO₂-based devices. It provides more active sites and a large interface for any type of reaction/interaction between the device and the interacting media. Thus, the performance of TiO₂-based devices is largely influenced by the size of TiO₂ building units. For example, high surface area TiO₂ nanomaterials can guarantee good accessibility and contact with the electrolyte in lithium-ion batteries. Small primary crystals offer short diffusion paths for lithium and are beneficial for short charging–discharging times in batteries. Anatase, which has a

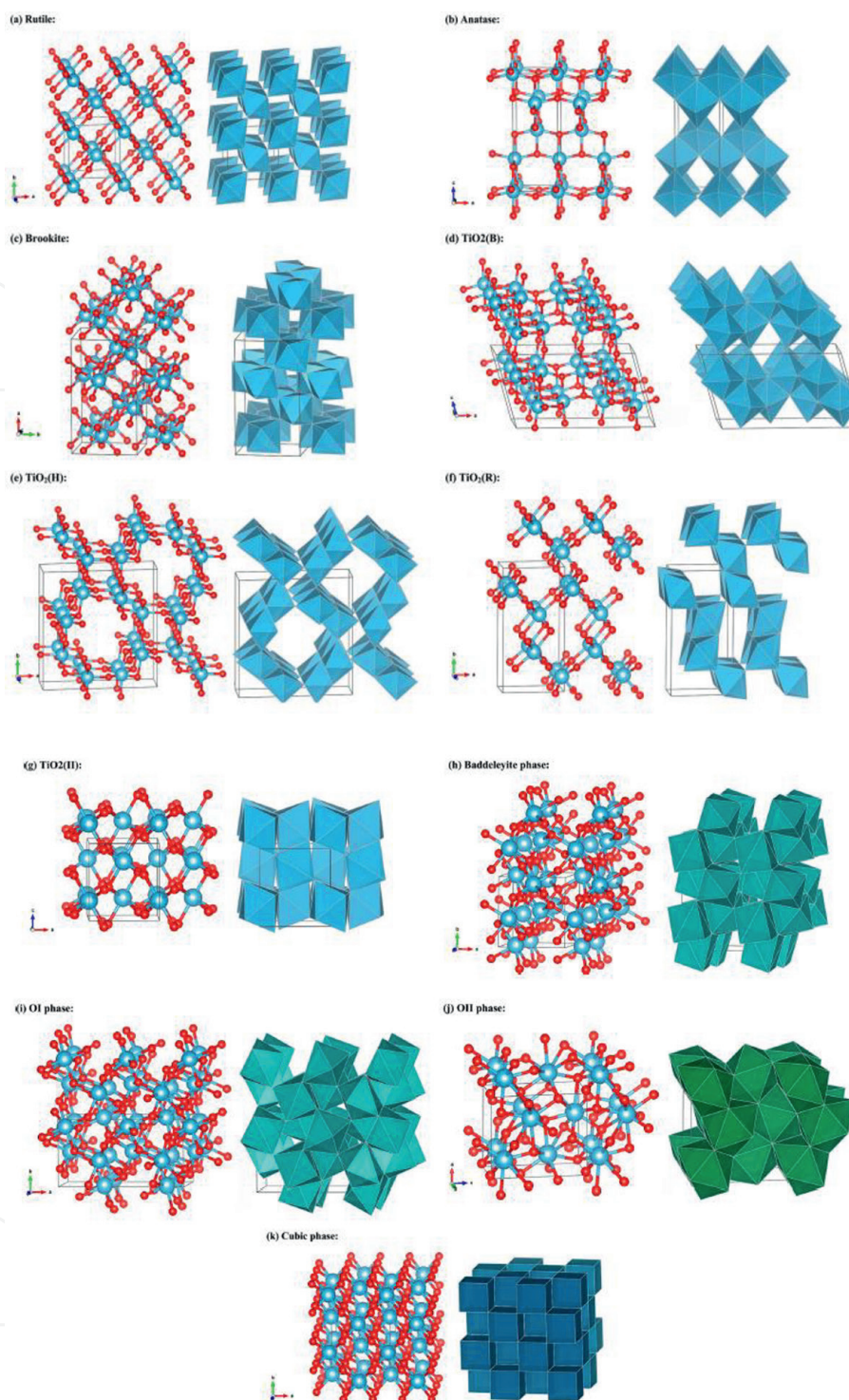


Figure 2. Structures of TiO_2 phases: (a) rutile, (b) anatase, (c) brookite, (d) TiO_2 (B), (e) TiO_2 (II), (f) TiO_2 (R), (g) TiO_2 (II), (h) baddeleyite TiO_2 , (i) TiO_2 -OI, (j) TiO_2 -OII and (k) cubic TiO_2 [32].

greater surface area than its counterparts, is widely used as a photocatalyst in photon–electron transfer, whereas rutile is used for light scattering [57]. Surface charge is an important property of nanoparticle dispersions. When nanoparticles are dispersed in an aqueous solution, surface ionization and adsorption of cations or anions generate a surface charge, creating an electric potential between the particle surface and the bulk of the dispersion medium [58]. Depending on the measurement technique, the surface charge can be expressed either as surface charge density (potentiometric

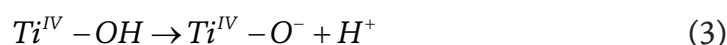
titration) or zeta potential (electrokinetic method). The point where the surface charge density is zero is defined as the point of zero charges (ZPC), and the point where the zeta potential is zero is defined as the isoelectric point (IEP) [58].

The surface of TiO₂ nanoparticles dispersed in aqueous media or humid atmosphere can react immediately with water molecules, and reasonable amounts of hydroxyl groups are formed as shown in Eq. 1 [30, 58].



When the surface of TiO₂ is fully hydroxylated, the oxide ions in the oxide and water absorbed on the surface would distribute electrons and form equal quantities of two types of hydroxyl groups [30].

The surface charge of titania is a function of solution pH, which is affected by the reactions that occur on the particle surface as shown in Eqs. 2 and 3.



A variety of nanostructured TiO₂ materials with fascinating morphologies have been reported. The synthesis methods used for the fabrication of these nanostructures have a significant effect on their dimensions. In general, nanostructure forms of TiO₂ have been classified into 0D (nanospheres, quantum dots), 1D (nanowires, rods, and tubes), 2D (layers and sheets), and 3D (nanoparticles, nanoflowers, etc.) architectures, which are summarized in **Figure 3** [61, 62].

Dissolution is defined as the dynamic process during which constituent molecules of the dissolving solid migrate from the surface to the bulk solution through a diffusion layer. The thermodynamic parameter that controls this process is described as solubility and along with the concentration gradient between the particle surface and the bulk, the solution acts as the driving force of particle dissolution [36]. Both solubility and rate of dissolution are dependent on a particle's chemical and surface properties such as surface area, surface morphology, and surface energy, as well as size. Crystallinity and crystal structure also need to be considered. They depend also on the possible adsorbed species, and the state of aggregation of the nanoparticles

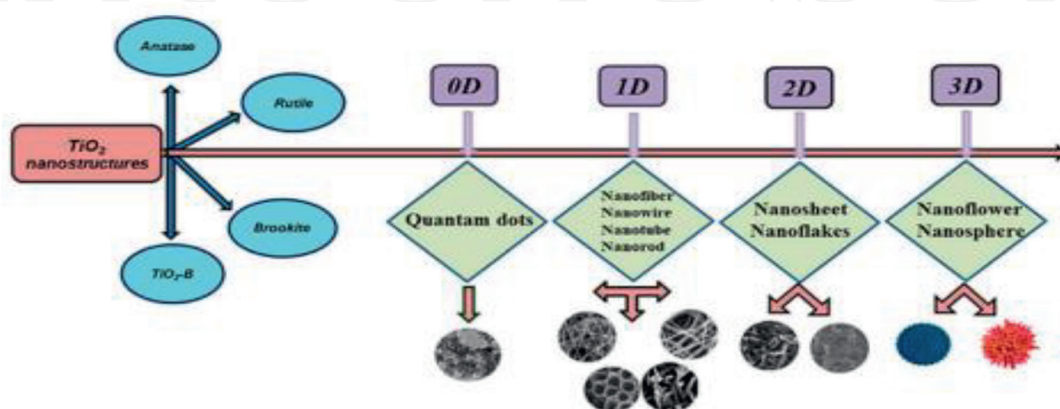


Figure 3.
 Categorization of hierarchical TiO₂ nanostructure form [59, 60].

and are further impacted by the surrounding media (properties of the diffusion layer and the possible solute concentration) [36, 63].

Studies have shown that TiO₂ nanoparticles tend to aggregate and their aggregation has a strong influence on nanoparticle behavior due to the nature and size of the aggregates (i.e., the packing density of the nanoparticles), and aggregation can potentially impact their reactivity, nanoparticle-cellular interactions, and toxicity [43]. There are two types of aggregations: homo-aggregation and hetero-aggregation. Homoaggregation refers to the aggregation of two particles of identical characteristics (i.e., NP–NP attachment). Heteroaggregation refers to the aggregation of particles with different physical or chemical characteristics (e.g., NP–clay particle attachment). In the natural environment of aquatic systems, the state of aggregation of the nanoparticles is greatly influenced by diverse conditions such as ionic strength (IS), ionic composition, co-existing colloids, natural organic matter (NOM) (e.g., humic fulvic and humic substances), pH, and other physicochemical factors [64].

4. Potential and applications of NS TiO₂

Metal oxide nanoparticles (NPs) have found a variety of applications in numerous industrial, medical, and environmental fields, attributable to recent advances in the nanotechnology field.

4.1 Photocatalytic applications

Photocatalysis is the decomposition and degradation of pollutants under the action of light rays on the surface of a catalyst, usually titanium dioxide (TiO₂). It allows the destruction of volatile organic compounds, inorganic pollutants, and microorganisms. The finalized process produces essential water and carbon dioxide [65]. All current applications of photocatalysis use TiO₂ as a semiconductor for several reasons [66]. Titanium dioxide, in its current commercial forms, is not toxic (apart from recent reservations about the use of nanoparticles) and, due to its photostability in air and water, does not release toxic elements [67]. As titanium is a relatively abundant element, the cost of TiO₂ is not too high, at least for some applications. The most widely used crystallographic form is the anatase form because TiO₂ with a rutile structure (although having a lower band gap value allowing it to absorb light in the early visible spectrum) is significantly less active. The most effective commercial composition at present is TiO₂ Degussa P25 (80% anatase, 20% rutile) [68]. For practical industrial applications of semiconductor photocatalysts, Sharma et al. [52] proved the development of research of new semiconductor materials in visible-light active TiO₂/SnX (X = S and Se) and their application as photocatalysts since it is a new area of scientific interest. Indeed, they focused on the addition of TiO₂ composites with SnX (X = S, Se) as potential candidates for environmental purification.

4.2 Photovoltaic applications

In the current global scenario, the rise in technological demands of the world's population has caused a rapid increase in energy consumption, which in turn has led to an exponential increase in environmental pollution, which we have witnessed seriously in the last decades. To surmount this situation, the efficient use of green energy has become a hot topic worldwide. On the other hand, intelligent materials

are also of great value in the current market due to their multipurpose for a variety of applications. Among the green energy alternatives available today, solar energy provides more promising perspectives as the sun can deliver the ultimate solution to the prevailing sustainable energy supply challenge. Among the different solar cell technologies currently available, dye-sensitized solar cells have drawn a lot of attention due to their promising prospects. On the Other Side, photocatalysis has also made a strong case for itself due to its promising opportunities for clean, green, and sustainable development in environmental technology applications [69, 70].

4.3 Sensing applications

In recent years, gas sensors have become extremely important for environmental and industrial atmosphere monitoring [71]. Gas detection techniques are based on resistance sensing, electrochemical and optical methods, gas and liquid chromatography, and acoustic waves. Nevertheless, certain sensors have various drawbacks: they consume energy and time, they are wide in size, they are expensive, and they display slow response and low selectivity [72, 73]. Consequently, special attention has been given to chemoresistive sensors, which are formed by metal oxides, carbon-based materials, and conducting polymers. Among these materials, semiconducting metal oxides have been extensively investigated and explored due to the potential for different valences, morphologies, and physicochemical characteristics [74]. They are becoming more complex than pure metals, with bonding going from ionic to highly covalent to metallic. For this reason, metal oxide nanoparticles are attracting considerable attention from industry for use in diverse applications such as catalytic processes, magnetic storage media, electronics, sensors, and solar energy conversion.

4.4 Hydrogen production and storage

Hydrogen (H₂) generation has become viral in the last few decades due to hydrogen as a future energy source and its capacity to replace expensive and polluting fossil fuels [75]. In addition, hydrogen also contributes to the development of a green world due to its zero emissions and minimizes dependence on non-renewable resources. In general, hydrogen production processes can be divided into two categories based on the usage of renewable and non-renewable resources. The methods for utilizing renewable energy resources are photoelectrolysis, thermal and photocatalytic water splitting, and steam reforming and gasification. Steam reforming and gasification methods are processes that depend on non-renewable resources [76]. Among carbon materials, activated carbon (AC) can be produced easily from agricultural residues such as hardwoods, coconut shells, fruit pits, walnut shells, and lignite. Which makes CA abundantly available and less expensive. CA also has characteristics such as a high surface area and a porous structure [77]. Such as high surface area and porous structure [77]. Due to these characteristics, AC-TiO₂ nanocomposites have been extensively investigated for the photocatalytic decomposition of dyes [78]. As an example, Mahadwad et al. [79] decomposed the reactive black dye 5 under mercury vapor light with AC-TiO₂ nanocomposites. Recently, Xing et al. [80] reported the H₂ generation activity with different types of simulated seawater with Rh/Cr₂O₃GaN nanowire photocatalyst [81]. Reddy et al. [82] have developed a low-cost nanocomposite such as AC-TiO₂ by a one-step hydrothermal method, which is a potential catalyst for H₂ generation under sunlight. In the photocatalytic H₂ generation process, sacrificial agents have a crucial role in consuming the valence band (VB) holes.

4.5 Environmental applications

TiO₂ is an environmental-friendly material that has been widely used in the photodegradation of a large number of pollutants. Nanostructured TiO₂ was used in pollution abatement, energy conversion (i.e. hydrogen production and solar cells), and energy storage (i.e. lithium batteries and supercapacitors). Its practical interest was also described in water purification, self-cleaning, self-sterilization of surfaces, as well as light-assisted H₂ production [83]. In the textile field, Gaminian and Montazer [84] assessed the self-cleaning effects of Cu₂O/TiO₂ on polyester fabric and concluded that both washed and unwashed samples showed significant photodegradation properties of methylene blue. Production of the reducing agent ethylene glycol as a product of the alkaline hydrolysis for the synthesis of Cu nanoparticles was reported indeed. In another trial, Harifi and Montazer [85] developed Fe³⁺-doped Ag/TiO₂ nanostructures for photocatalytic uses under the UV-vis light spectrum. The photodegradation activity assessed using methylene blue was confirmed under both UV and visible light regions. Zhou et al. [86] explored the degradation of acetone in the air using iron-doped mesoporous TiO₂ nanoparticles. Their findings showed a high degradation rate of this organic pollutant. In the same way, El-Roz et al. [87] reported an enhanced photocatalytic activity of luffa/TiO₂ nanocomposites against methanol. Pištková et al. [88] investigated the photodecomposition of acebutolol, propranolol, atenolol, nadolol, and metoprolol, which are β-blockers, using immobilized TiO₂ in an aqueous media. Their results showed a complete photodegradation in 2 h of all tested β-blockers. Coronado et al. [89] described some TiO₂ applications in water purification. This application is argued by the excellent optical and catalytic properties of nanostructured TiO₂, allowing oxidation and reduction catalysis of both organic and inorganic contaminants. The photo-generated free radicals and e⁻/h⁺ pairs are highly implicated in degrading organic substances, water pollutants, and harmful microorganisms [90]. In this trend, nanocomposite TiO₂ thin films (P/Ag/Ag₂O/Ag₃PO₄) were able to decompose up to 90% of rhodamine B under solar light exposure [91, 92].

4.6 Biomedical applications

Nanomedicine is defined as “the development of nanoscale (1–100 nm) or nanostructured objects/nano-robots/skin patches and their use in medicine for diagnostic and therapeutic purposes based on the use of their structure, which has unique medical effects” [93]. It relies on the use of nanodevices and nanostructures operating at the cellular level, providing therefore comprehensive monitoring, control, repair, and enhancement of biological systems at the molecular level. The use of nanoparticles is deep-rooted in the history of medicine. The application of nanosilver to overcome bacterial infections and the use of nanosized agents to modulate immune response are some examples. TiO₂ nanostructures are one of the most plentiful nanomaterials having a broad spectrum of applications in nanomedicine. TiO₂ is not only a cost-effective and highly biocompatible nanoparticle [94], but it is also a non-toxic substance [95], which use in food and drugs has been approved by the American Food and Drug Administration (FDA) to be [96].

5. Future challenges and perspectives

In this chapter, the use of nanostructured titanium dioxide is an effective and attractive alternative for fabricating flexible devices for multiple applications, which

can be explored based on TiO₂ properties, fabrication, and modification. A further challenge is to enhance the spectral sensitivity of these structures to the visible and near-infrared regions and the biocompatibility of TiO₂ nanostructures. Therefore, future studies focused on long-term, constant photoactivity are greatly needed. These can be achieved by changing the synthesis route. Nonmetal-doped TiO₂ nanostructures exhibit low photocatalytic activity under visible UV light. Some materials, such as polymers, glasses, ceramics, and metals, therefore serve as magical identities for economical and environmentally friendly applications in this field. Future research requires the development of new synthetic methods and nanostructures with higher surface states. This can be serviced by techniques compatible with non-lithographic complementary metal oxide semiconductors. This technique has potential applications in new dopant materials, incorporation of dopants into TiO₂ nanostructures, and environmental and alternative energy applications. Therefore, there is a great need to improve the structure and properties of these materials. Basic knowledge of chemistry, physics, and computer modeling will help you accomplish your task.

6. Conclusion

Many reviews and reports have been published on various aspects such as the properties, production, modification, and application of titanium dioxide. This chapter provided a detailed overview of the synthesis, properties, and applications of nanostructured titanium dioxide (NS-TiO₂). Moreover, Titanium dioxide nanoparticles have gained a lot of attention because of their numerous applications. The formation of TiO₂ from various biological sources (plants, microorganisms, and related bioproducts) has been discussed. Furthermore, the mechanism of their uptake, translocation, and accumulation in plants is explored. The potential impact of TiO₂ has also been reported. Titanium dioxide nanoparticles have found a variety of applications in numerous industrial, medical, and environmental fields, attributable to recent advances in the nanotechnology field.

IntechOpen

IntechOpen

Author details

Bochra Bejaoui^{1,2*}, Imen Bouchmila¹, Khaoula Nefzi³, Imen Belhadj Slimen⁴, Sidrine Koumbad⁵, Patrick Martin⁵, Nicolas Joly⁵ and Naceur M'Hamdi⁶

1 National Institute of Research and Pysico-chemical Analysis (INRAP), Laboratory of Useful Materials, Technopark of Sidi Thabet, Ariana, Tunisia

2 Faculty of Sciences of Bizerte, University of Carthage, Department of Chemistry, Zarzouna, Bizerte, Tunisia

3 Carthage University, National Research Institute of Rural Engineering, Water and Forests (INRGREF), LR11INRGREF0 Laboratory of Management and Valorization of Forest Resources, Ariana, Tunisia


4 Department of Animal Sciences, National Agronomic Institute of Tunisia, Carthage University, Tunis, Tunisia

5 Unité Transformations and Agroressources, Université d'Artois-Uni LaSalle, Bethune, France

6 Research Laboratory of Ecosystems and Aquatic Resources, National Agronomic Institute of Tunisia, Carthage University, Tunis, Tunisia

*Address all correspondence to: bochrabej@yahoo.fr

IntechOpen

© 2023 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Ali I, Suhail M, Alothman ZA, Alwarthan A. Recent advances in syntheses, properties, and applications of TiO₂ nanostructures. *RSC Advances*. 24 Aug 2018;**8**(53):30125-30147. DOI: 10.1039/c8ra06517a
- [2] Pfaff G, Reynders P. Angle-dependent optical effects deriving from submicron structures of films and pigments. *Chemical Reviews*. 1999;**99**(7):1963-1981
- [3] Newman MD, Stotland M, Ellis JI. The safety of nanosized particles in titanium dioxide- and zinc oxide-based sunscreens. *Journal of the American Academy of Dermatology*. 2009;**61**(4):685-692
- [4] Salvador A, Pascual-Martı MC, Adell JR, Requeni A, March JG. Analytical methodologies for atomic spectrometric determination of metallic oxides in UV sunscreen creams. *Journal of Pharmaceutical and Biomedical Analysis*. 2000;**22**(2):301-306
- [5] Fujishima A, Honda K. Electrochemical photolysis of water at a semiconductor electrode. *Nature*. 1972;**238**(5358):37-38
- [6] Patri A, Umbreit T, Zheng J, Nagashima K, Goering P, Francke-Carroll S, et al. Energy dispersive X-ray analysis of titanium dioxide nanoparticle distribution after intravenous and subcutaneous injection in mice. *Journal of Applied Toxicology: An International Journal*. 2009;**29**(8):662-672
- [7] Sul Y-T. Electrochemical growth behavior, surface properties, and enhanced in vivo bone response of TiO₂ nanotubes on microstructured surfaces of blasted, screw-shaped titanium implants. *International Journal of Nanomedicine*. 2010:87-100
- [8] Auguglia V, Caronna T, Paola A, Marci G, Pagliaro M, Palmisano G, et al. *Environmentally Benign Photocatalysts*. New York: Springer; 2010. pp. 623-645
- [9] Rossi S, Savi M, Mazzola M, Pinelli S, Alinovi R, Gennaccaro L, et al. *Particle and Fibre Toxicology*. 2019;**16**:1
- [10] Zada A, Qu Y, Ali S, Sun N, Lu H, Yan R, et al. Improved visible-light activities for degrading pollutants on TiO₂/g-C₃N₄ nanocomposites by decorating SPR Au nanoparticles and 2,4-dichlorophenol decomposition path. *Journal of Hazardous Materials*. 2018;**342**:715-723
- [11] Zhao L, Zhu Y, Chen Z, Xu H, Zhou J, Tang S, et al. *Nanotoxicology*. 2018;**12**:169
- [12] Ali W, Ullah H, Zada A, Muhammad W, Ali S, Shaheen S, et al. Synthesis of TiO₂ modified self-assembled honeycomb ZnO/SnO₂ nanocomposites for exceptional photocatalytic degradation of 2,4-dichlorophenol and bisphenol A. *Science of the Total Environment*. 2020;**746**:141291
- [13] Ali S, Li Z, Chen S, Zada A, Khan I, Khan I, et al. Synthesis of activated carbon-supported TiO₂-based nano-photocatalysts with well recycling for efficiently degrading high-concentration pollutants. *Catalysis Today*. 2019;**335**:557-564
- [14] Kozlova EA, Rempel AA, Valeeva AA, Gorbunova TI, Kozhevnikova NS, Cherepanova SV, et al. Photoactivity of TiO₂/CdS and SiO₂/CdS hybrid nanostructured systems in the partial oxidation of ethanol under irradiation with visible light. *Kinetics and Catalysis*. 2015;**56**:515-522

- [15] Liu C, Raziq F, Li Z, Qu Y, Zada A, Jing L. Synthesis of TiO₂/g-C₃N₄ nanocomposites with phosphate-oxygen functional bridges for improved photocatalytic activity. *Chinese Journal of Catalysis*. 2017;**38**(6):1072-1078
- [16] Utepova IA, Trestsova MA, Chupakhin ON, Charushin VN, Rempel AA. *Green Chemistry*. 2015;**17**:4401
- [17] Utepova IA, Chupakhin ON, Trestsova MA, Khina AAM, Kucheryavaya DA, Charushin VN, et al. *Russian Chemical Bulletin*. 2016;**65**:445
- [18] Liu S, Chen X, Yu M, Li J, Liu J, Xie Z, et al. Applications of titanium dioxide nanostructure in stomatology. *Molecules*. 2022;**27**:3881. DOI: 10.3390/molecules27123881
- [19] Cuddy MF, Poda AR, Moser RD, Weiss CA, Cairns C, Steevens JA. A weight-of-evidence approach to identify nanomaterials in consumer products: A case study of nanoparticles in commercial sunscreens. *Journal of Exposure Science & Environmental Epidemiology*. 2016;**26**:26-34
- [20] Shah R, Ali S, Raziq F, Ali S, Ismail PM, Shah S, et al. Exploration of metal organic frameworks and covalent organic frameworks for energy-related applications. *Coordination Chemistry Reviews*. 2023;**477**:214968
- [21] Weir A, Westerhoff P, Fabricius L. Titanium dioxide nanoparticles in food and personal care products. *Environmental Science & Technology ES&T*. 2012;**46**:2242-2250
- [22] Ai JW, Liu B, Liu WD. Folic acid-tagged titanium dioxide nanoparticles for enhanced anticancer effect in osteosarcoma cells. *Materials Science & Engineering. C, Materials for Biological Applications*. 2017;**76**:1181-1187
- [23] Ding L, Li J, Huang R, Liu Z, Li C, Yao S, et al. Salvianolic acid B protects against myocardial damage caused by nanocarrier TiO₂; and synergistic anti-breast carcinoma effect with curcumin via codelivery system of folic acid-targeted and polyethylene glycol-modified TiO₂ nanoparticles. *International Journal of Nanomedicine*. 2016;**11**:5709-5727
- [24] Jia L, Qiu J, Du L, Li Z, Liu H, Ge S. TiO₂ nanorod arrays as a photocatalytic coating enhanced antifungal and antibacterial efficiency of Ti substrates. *Nanomedicine*. 2017;**12**:761-776
- [25] Das K, Bose S, Bandyopadhyay A. TiO₂ nanotubes on Ti: Influence of nanoscale morphology on bone cell-materials interaction. *Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials*. 2009;**90**(1):225-237
- [26] Garcia-Lobato M, Mtz-Enriquez A, Garcia C, Velazquez-Manzanares M, Avalos-Belmontes F, Ramos-Gonzalez R, et al. *Applied Surface Science*. 2019;**484**:975
- [27] Wang N, Li H, Lü W, Li J, Wang J, Zhang Z, et al. *Biomaterials*. 2011;**32**:690
- [28] Bezerra IA, Neta MF, Mota HL, Lira GA, Neves RRM. Nanostructured titanium dioxide for use in bone implants: A short review. *Cerâmica*. 2020;**66**(380)
- [29] Zada A, Khan M, Khan MA, Khan Q, Yangjeh AH, Dang A, et al. Review on the hazardous applications and photodegradation mechanisms of chlorophenols over different photocatalysts. *Environmental Research*. 2021;**195**:110742
- [30] Arun J, Nachiappan S, Rangarajan G, Alagappan RP, Gopinath KP, Lichtfouse E.

Synthesis and application of titanium dioxide photocatalysis for energy, decontamination, and viral disinfection: A review. *Environmental Chemistry Letters*. 2022, 2022. DOI: 10.1007/s10311-022-01503-z

[31] Kumar A, Pandey G. Different methods used for the synthesis of TiO₂ based nanomaterials: A review. *American Journal of Nano Research and Applications*. 2018;**6**(1):1-10

[32] Nyamukamba P, Okoh O, Heroe H, Taziwa R, Zinya S. *Synthetic Methods for Titanium Dioxide Nanoparticles: A Review*. Titanium Dioxide-material for a Sustainable Environment. 2018

[33] Mehrotra RC, Singh A. Recent trends in metal alkoxide chemistry. In: *Progress in Inorganic Chemistry*. John Wiley & Sons, Ltd; 1997. pp. 239-454. DOI: 10.1002/9780470166475.ch4

[34] Kaur N, Singh M, Moumen A, Duina G, Comini E. 1D titanium dioxide: Achievements in chemical sensing. *Materials (Basel)*. 2020;**13**:2974

[35] Liu N, Chen X, Zhang J, Schwank JW. A review on TiO₂-based nanotubes synthesized via hydrothermal method: Formation mechanism, structure modification, and photocatalytic applications. *Catalysis Today*. 2014;**225**:34-51

[36] Guo R, Bao Y, Kang Q, Liu C, Zhang W, Zhu Q. Solvent-controlled synthesis and photocatalytic activity of hollow TiO₂ microspheres prepared by the solvothermal method. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2022;**633**:127931

[37] Kathirvel S, Pedaballi S, Su C, Chen B-R, Li W-R. Morphological control of TiO₂ nanocrystals by solvothermal synthesis for dye-sensitized solar cell

applications. *Applied Surface Science*. 2020;**519**:146082

[38] Li Z-Q, Chen W-C, Guo F-L, Mo L-E, Hu L-H, Dai S-Y. Mesoporous TiO₂ yolk-shell microspheres for dye-sensitized solar cells with a high efficiency exceeding 11%. *Scientific Reports*. 2015;**5**(14178):1-8

[39] Li G, Song J, Meng C, Wang D, Du Z, Sun W, et al. Single source, surfactant-free, and one-step solvothermal route synthesized TiO₂ microspheres for highly efficient mesoscopic perovskite solar cells. *Solar RRL*. 2020;**4**:2000519

[40] Melo ACCA, De Jeus RA, Olivera de M, Claudia A, et al. Effect of non-ionic surfactant in the solvothermal synthesis of anatase TiO₂ nanoplates with a high percentage of exposed {001} facets and its role in the photocatalytic degradation of methylene blue dye. *Environmental Research*. 2022;**214**:114094

[41] Paschalidou P, Theocharis CR. Tuning the porosity and surface characteristics of nanoporous titania using non-ionic surfactant reverse micelles. *RSC Advances*. 2018;**8**(52):29890-29898

[42] Qiao L, Swihart MT. Solution-phase synthesis of transition metal oxide nanocrystals: Morphologies, formulae, and mechanisms. *Advances in Colloid and Interface Science*. 2017;**244**:199-266

[43] Lepcha A, Maccato C, Mettenbörger A, Andreu T, Mayrhofer L, Walter M, et al. Electrospun black titania nanofibers: Influence of hydrogen plasma-induced disorder on the electronic structure and photoelectrochemical performance. *The Journal of Physical Chemistry C. American Chemical Society*. 2015;**119**:18835-18842

[44] Perraudon A, Dublanche-Tixier C, Tristant P, Chazelas C. Dynamic mode optimization for the deposition

- of homogeneous TiO₂ thin film by atmospheric pressure PECVD using a microwave plasma torch. *Applied Surface Science*. 2019;**493**:703-709
- [45] Mohan L, Dennis C, Padmapriya N, Anandan C, Rajendran N. Effect of electrolyte temperature and anodization time on formation of TiO₂ nanotubes for biomedical applications. *Materials Today Communications*. 2020;**23**:101103
- [46] Wu J-M. Low-temperature preparation of titania nanorods through direct oxidation of titanium with hydrogen peroxide. *Journal of Crystal Growth*. 2004;**269**:347-355
- [47] Kamali M, Dewil R, Appels L, Aminabhavi TM. Nanostructured materials via green sonochemical routes - Sustainability aspects. *Chemosphere*. 2021;**276**:130146
- [48] Savun B. A review on sonochemistry and its environmental applications. *Acoustics*. 2020;**2**:766-775
- [49] Moreira AJ, Campos LO, Maldini CP, Dias JA, Paris EC, Giraldi TR, et al. Photocatalytic degradation of Prozac® mediated by TiO₂ nanoparticles obtained via three synthesis methods: Sonochemical, microwave hydrothermal, and polymeric precursor. *Environmental Science and Pollution Research*. 2020;**27**:27032-27047
- [50] Zhu Y-J, Chen F. Microwave-assisted preparation of inorganic nanostructures in liquid phase. *Chemical Review*. American Chemical Society. 2014;**114**:6462-6555
- [51] Sadek O, Touhtouh S, Rkhis M, Anoua R, El Jouad M, Belhora F, et al. Synthesis by sol-gel method and characterization of nano-TiO₂ powders. *Materials Today: Proceedings*. 2022;**66**:456-458
- [52] Sharma R, Sarkar A, Jha R, Kumar Sharma A, Sharma D. Sol-gel-mediated synthesis of TiO₂ nanocrystals: Structural, optical, and electrochemical properties. *International Journal of Applied Ceramic Technology*. 2020;**17**:1400-1409
- [53] Nateq MH, Ceccato R. Sol-gel synthesis of TiO₂ nanocrystalline particles with enhanced surface area through the reverse micelle approach. *Advances in Materials Science and Engineering*. Hindawi. 2019;**2019**:e1567824
- [54] Lukong VT, Ukoba KO, Jen TC. Heat-assisted sol-gel synthesis of TiO₂ nanoparticles structural, morphological, and optical analysis for self-cleaning application. *Journal of King Saud University - Science*. 2022;**34**:101746
- [55] Keshari AK, Choudhary P, Shukla VK. Precursor-induced evolution in single anatase phase synthesis of TiO₂ nanoparticles for water treatment and dye-sensitized solar cell. *Physica B: Condensed Matter*. 2022;**631**:413716
- [56] Lu H, Zhong J, Ji C, Zhao J, Li D, Zhao R, et al. Fabricating an optimal rutile TiO₂ electron transport layer by delicately tuning TiCl₄ precursor solution for high-performance perovskite solar cells. *Nano Energy*. 2020;**68**:104336
- [57] Kaur A, Bajaj B, Kaushik A, Saini A, Sud D. A review on template-assisted synthesis of multi-functional metal oxide nanostructures: Status and prospects. *Materials Science and Engineering: B*. 2022;**286**:116005
- [58] Allende P, Orera A, Laguna-Bercero MÁ, Valenzuela ML, Díaz C, Barrientos L. Insights of the formation mechanism of nanostructured titanium oxide polymorphs from different macromolecular metal-complex precursors. *Heliyon*. 2021;**7**:e07684

- [59] Dharma HNC, Jaafar J, Widiastuti N, Matsuyama H, Rajabsadeh S, Othman MHD, et al. A review of titanium dioxide (TiO₂)-based photocatalyst for oilfield-produced water treatment. *Membranes*. 2022;**12**(3):345
- [60] Reghunath S, Pinheiro D, KR SD. A review of hierarchical nanostructures of TiO₂: Advances and applications. *Applied Surface Science Advances*. 2021;**3**:100063
- [61] Quintero Y, Mosquera E, Diosa J, García A. Ultrasonic-assisted sol-gel synthesis of TiO₂ nanostructures: Influence of synthesis parameters on morphology, crystallinity, and photocatalytic performance. *Journal of Sol-Gel Science and Technology*. 2020;**94**:477-485
- [62] Razak KA, et al. Factors of controlling the formation of titanium dioxide (TiO₂) synthesized using sol-gel method – A short review. *Journal of Physics: Conference Series*. IOP Publishing. 2022;**2169**(1)
- [63] Cao R, Gao J, Tao H. One-step hydrothermal synthesis of multiphase nano TiO₂. *Materials Letters*. 2022;**317**:132121
- [64] Khizir HA, Abbas TA-H. Hydrothermal synthesis of TiO₂ nanorods as sensing membrane for extended-gate field-effect transistor (EGFET) pH sensing applications. *Sensors and Actuators A: Physical*. 2022;**333**:113231
- [65] Basavarajappa PS, Patil SB, Ganganagappa N, Reddy KR, Raghu AV, Reddy CV. Recent progress in metal-doped TiO₂, non-metal-doped/codoped TiO₂, and TiO₂ nanostructured hybrids for enhanced photocatalysis. *International Journal of Hydrogen Energy*. 2020;**45**(13):7764-7778
- [66] Zhao Y, Linghu X, Shu Y, Zhang J, Chen Z, Wu Y, et al. Classification and catalytic mechanisms of heterojunction photocatalysts and the application of titanium dioxide (TiO₂)-based heterojunctions in environmental remediation. *Journal of Environmental Chemical Engineering*. 2022;**10**:108077
- [67] Crețescu I, Lutić D. Advanced removal of crystal violet dye from aqueous solutions by photocatalysis using commercial products containing titanium dioxide. *Comptes Rendus Chimie*. 2022;**25**(S3):1-12
- [68] Qin S, Denisov N, Sarma BB, Hwang I, Doronkin DE, Tomanec O, et al. Pt single atoms on TiO₂ polymorphs—Minimum loading with a maximized photocatalytic efficiency. *Advanced Materials Interfaces*. 2022;**9**(22):2200808
- [69] Calogero G, Bartolotta A, Di Marco G, Di Carlo A, Bonaccorso F. Vegetable-based dye-sensitized solar cells. *Chemical Society Reviews*. 2015;**44**(10):3244-3294. DOI: 10.1039/c4cs00309h
- [70] Ukoba KO, Eloka-Eboka AC, Inambao FL. Review of solar energy inclusion in Africa: A case study of Nigeria. 2017
- [71] Ren P, Qi L, You K, Shi Q. Hydrothermal synthesis of hierarchical SnO₂ nanostructures for improved formaldehyde gas sensing. *Nanomaterials*. 2022;**12**:228
- [72] Biswas P, Zhang C, Chen Y, Liu Z, Vaziri S, Zhou W, et al. A portable micro-gas chromatography with integrated photonic crystal slab sensors on chip. *Biosensors*. 2021;**11**:236
- [73] Zampolli S, Elmi I, Cardinali GC, Masini L, Bonafè F, Zardi F. Compact-GC platform: A flexible system integration strategy for a completely microsystems-based gas-chromatograph. *Sensors and Actuators B: Chemical*. 2020;**305**:127444

- [74] Zhai T, Fang X, Liao M, Xu X, Zeng H, Yoshio B, et al. A comprehensive review of one-dimensional metal-oxide nanostructure photodetectors. *Sensors*. 2009;**9**:6504-6529
- [75] Sadanandam G, Lalitha K, Kumari VD, Shankar MV, Subrahmanyam M. Cobalt-doped TiO₂: A stable and efficient photocatalyst for continuous hydrogen production from glycerol: Water mixtures under solar light irradiation. *International Journal of Hydrogen Energy*. 2013;**38**:9655-9664. DOI: 10.1016/j.ijhydene.2013.05.116
- [76] Ramesh RN, Bhargav U, Mamatha Kumari M, Cheralathan KK, Sakar M. Review on the interface engineering in the carbonaceous titania for the improved photocatalytic hydrogen production. *International Journal of Hydrogen Energy*. 2020;**45**:7584-7615. DOI: 10.1016/j.ijhydene.2019.09.041
- [77] Soliman AM, Elwy HM, Thiemann T, Majedi Y, Labata FT, AlRawashdeh NAF. Removal of Pb(II) ions from aqueous solutions by sulphuric acid-treated palm tree leaves. *Journal of the Taiwan Institute of Chemical Engineers*. 2016;**58**:264-273. DOI: 10.1016/j.jtice.2015.05.035
- [78] Singh J, Sahu K, Pandey A, Kumar M, Ghosh T, Satpati B, et al. Atom beam sputtered Ag-TiO₂ plasmonic nanocomposite thin films for photocatalytic applications. *Applied Surface Science*. 2017;**411**:347-354
- [79] Mahadwad OK, Parikh PA, Jasra RV, Patil C. Photocatalytic degradation of reactive black-5 dye using TiO₂ impregnated ZSM-5. *Bulletin of Materials Science*. 2011;**34**:551-556
- [80] Xing X, Zhu H, Zhang M, Xiao L, Li Q, Yang J. Effect of heterojunctions and phase-junctions on visible-light photocatalytic hydrogen evolution in BCN-TiO₂ photocatalysts. *Chemical Physics Letters*. 2019;**727**:11-18
- [81] Guan X, Chowdhury FA, Pant N, Guo L, Vayssieres L, Mi Z. Efficient unassisted overall photocatalytic seawater splitting on GaN-based nanowire arrays. *Journal of Physical Chemistry C*. 2018;**122**:13797-13802. DOI: 10.1021/acs.jpcc.8b00875
- [82] Reddy NR, Bharagav U, Kumari MM, Cheralathan KK, Ojha PK, Shankar MV, et al. Inclusion of low-cost activated carbon for improving hydrogen production performance of TiO₂ nanoparticles under natural solar light irradiation. *Ceramics International*. 2021;**47**(7):10216-10225
- [83] Fujishima A, Zhang X, Tryk DA. TiO₂ photocatalysis and related surface phenomena. *Surface Science Reports*. 2008;**63**:515-582
- [84] Gaminian H, Montazer M. Enhanced self-cleaning properties on polyester fabric under visible light through a single-step synthesis of cuprous oxide doped nano-TiO₂. *Photochemistry and Photobiology*. 2015;**91**:1078-1087
- [85] Harifi T, Montazer M. Fe³⁺: Ag/TiO₂ nanocomposite: Synthesis, characterization, and photocatalytic activity under UV and visible light irradiation. *Applied Catalysis A*. 2014;**473**:104-115
- [86] Zhou M, Yu J, Cheng B, Yu H. Preparation and photocatalytic activity of Fe-doped mesoporous titanium dioxide nanocrystalline photocatalysts. *Materials Chemistry and Physics*. 2005;**93**:159-163
- [87] El-Roz M, Haidar Z, Lakiss L, Toufaily J, Thibault-Starzyk F. Immobilization of TiO₂ nanoparticles on natural *Luffa cylindrica* fibers for photocatalytic applications. *RSC Advances*. 2013;**3**:3438-3445

- [88] Píšťková V, Tasbihi M, Vávrová M, Štangar UL. Photocatalytic degradation of β -blockers by using immobilized titania/silica on glass slides. *Journal of Photochemistry and Photobiology A: Chemistry*. 2015;**305**:19-28
- [89] Coronado JM, Sanchez B, Portela R, Suarez S. Influence of catalyst properties and reactor configuration on the photocatalytic degradation of trichloroethylene under sunlight irradiation. *Journal of Solar Energy Engineering, Transactions of the ASME*. 2008;**130**:041012
- [90] Selmi W, Hosni N, Naceur JB, Maghraoui-Meherzi H, Chtourou R. Titanium Dioxide Thin Films for Environmental Applications. In: *Titanium Dioxide - Advances and Applications*. London, United Kingdom: IntechOpen; 2022
- [91] Yan S, Li Y, Xie F, Wu J, Jia X, Yang J, et al. Environmentally safe and porous MS@TiO₂@PPy monoliths with superior visible-light photocatalytic properties for rapid oil-water separation and water purification. *ACS Sustainable Chemistry & Engineering*. 2020;**8**:5347-5359
- [92] Zhu Q, Hu X, Stanislaus MS, Zhang N, Xiao R, Liu N, et al. A novel P/Ag/Ag₂O/Ag₃PO₄/TiO₂ composite film for water purification and antibacterial application under solar light irradiation. *Science of the Total Environment*. 2017;**577**:236-244
- [93] Guin D, Thakran S, Singh P, Ramachandran S, Hasija Y, Kukreti R. Chapter 1 - Translational biotechnology: A transition from basic biology to evidence-based research. In: *Translational Biotechnology*. Hasija Y, editor. Elsevier, Academic Press; 2021:3-24
- [94] Molaeirad A, Janfaza S, Karimi-Fard A, Mahyad B. Photocurrent generation by adsorption of two main pigments of halobacterium salinarum on TiO₂ nanostructured electrode. *Biotechnology and Applied Biochemistry*. 2015;**62**:121-125
- [95] McCullagh C, Robertson JM, Bahnemann DW, Robertson PK. The application of TiO₂ photocatalysis for disinfection of water contaminated with pathogenic micro-organisms: A review. *Research on Chemical Intermediates*. 2007;**33**:359-375
- [96] Bonetta S, Bonetta S, Motta F, Strini A, Carraro E. Photocatalytic bacterial inactivation by TiO₂-coated surfaces. *AMB Express*. 2013;**3**:59