Chapter

Nanostructured Titanium Dioxide ($NS-TiO_2$)

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 TiO_2) has become tremendous. NS TiO_2 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 TiO_2 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 TiO_2, their chemical and surface modifications, and their application. The preparation of NS TiO_2, 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 TiO_2 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, TiO_2 nanostructures are the most attractive materials in modern science and technology [1]. TiO_2 is used commercially in donuts, cosmetics, pigments [2], catalysts, sunscreens [3, 4], solar cells [5], water splitting, and more. TiO_2 is used in plastics, paints, varnishes, paper, pharmaceuticals, inks, pharmaceuticals, toothpaste, food, and industry [6, 7]. Nanostructured titanium dioxide (NS-TiO_2) is a non-toxic, environmentally friendly, inexpensive, and efficient functional material with a broad range of applications [8–11]. In the past decade, nanostructured TiO_2, 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, TiO_2 nanostructures are the best-looking materials in modern science and technology [1]. Nano-TiO_2 nanostructures include titanium dioxide nanoparticles (TiO_2-NPs) and titanium dioxide nanotubes (TNTs) [18]. With the advent of nanotechnology, NS–TiO_2 has found many applications. Nanoscale titanium dioxide (nano-TiO_2) 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-TiO_2 has more stable physical and chemical properties compared to titanium dioxide. In addition, nano-TiO_2 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 TiO_2 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–TiO_2, 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 TiO_2 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-TiO_2). With the advent of nanotechnology, NS-TiO_2 has found many applications.

2. Synthesis process of NS TiO_2

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 TiO_2 nanostructures [12, 15]. In this section, we will analyze the most used methods for the preparation of TiO_2 nanostructures.

2.1 Chemical and physical methods

2.1.1 Sol: gel process

Sol-gel is a versatile method used for the synthesis of TiO_2 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

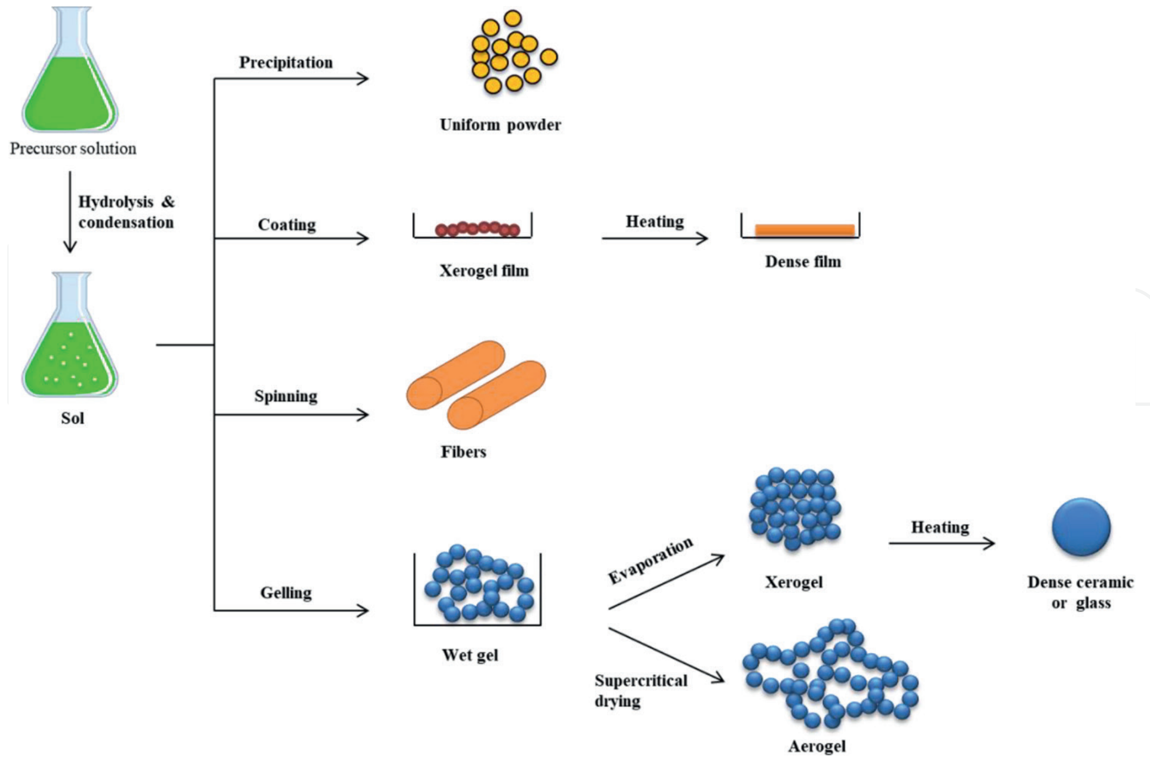

Figure 1.
Sol-gel process steps for the synthesis of TiO_2 nanostructures [30, 32, 33].

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 TiO_2 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 TiO_2 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 TiO_2 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 TiO_2 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 TiO_2 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 TiO_2. 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 Na_2SO_4) 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 TiO_2 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 chaffing: 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 TiO_2

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 TiO_2 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 TiO_2 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 (TiO_2), ilmenite ($FeTiO_3$), and titanite ($CaTiSiO_5$) [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 TiO_2 phases: a low-density amorphous TiO_2 and two high-density amorphous TiO_2 types. TiO_2 (II) and TiO_2 (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 m^2cm^{-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 TiO_2-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 TiO_2-based devices is largely influenced by the size of TiO_2 building units. For example, high surface area TiO_2 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

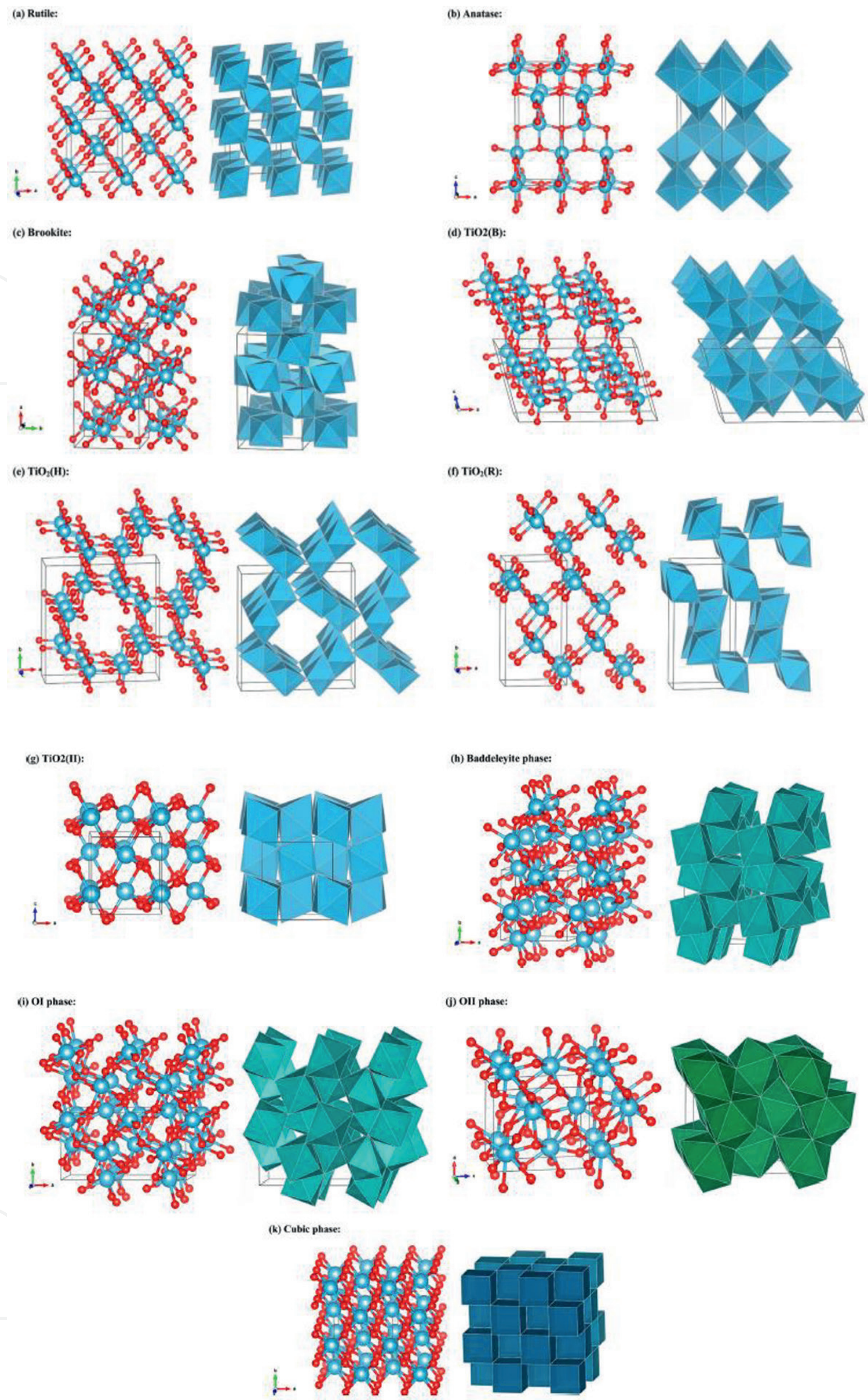

Figure 2.
Structures of TiO_2 phases: (a) rutile, (b) anatase, (c) brookite, (d) TiO_2 (B), (e) TiO_2 (II), (f) TiO_2(R), (g) TiO_2 (II), (h) baddeleyite TiO_2, (i) TiO_2-OI, (j) TiO_2-OII and (f) cubic TiO_2 [32].

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 TiO_2 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].

$$Ti^{IV} + H_2O \rightarrow Ti^{IV} - OH + H^+ \quad (1)$$

When the surface of TiO_2 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.

$$Ti^{IV} - OH + H^+ \rightarrow Ti^{IV} - OH_2^{\ +} \quad (2)$$

$$Ti^{IV} - OH \rightarrow Ti^{IV} - O^- + H^+ \quad (3)$$

A variety of nanostructured TiO_2 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 TiO_2 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

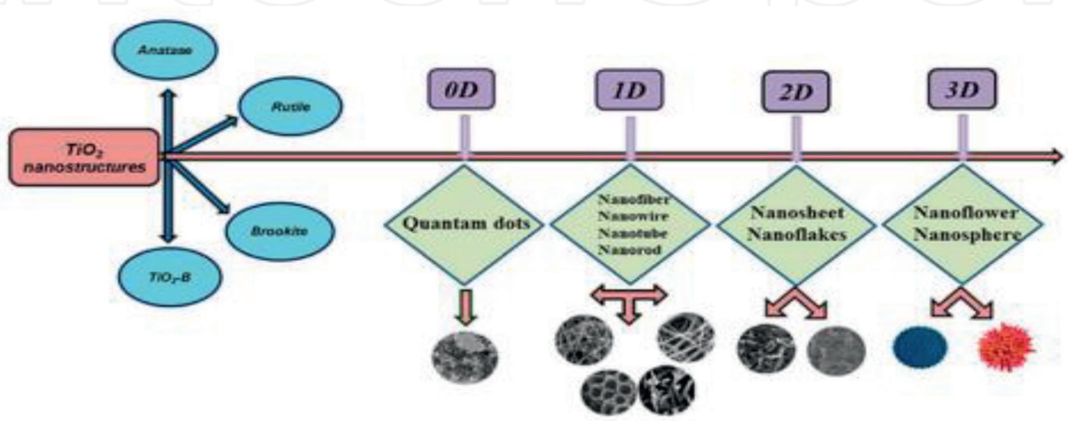

Figure 3.
Categorization of hierarchical TiO_2 nanostructure form [59, 60].

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

Studies have shown that TiO_2 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 y fulvic and humic substances), pH, and other physicochemical factors [64].

4. Potential and applications of NS TiO_2

Metal oxide nanoparticles (NPs) have found a variety of applications in numerous industrial, medical, and environmental fields s, 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 (TiO_2). 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 TiO_2 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 reservations regarding 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 TiO_2 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 TiO_2 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 TiO_2/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 TiO_2 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 (H_2) 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-TiO_2 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-TiO_2 nanocomposites. Recently, Xing et al. [80] reported the H_2 generation activity with different types of simulated seawater with Rh/Cr_2O_3GaN nanowire photocatalyst [81]. Reddy et al. [82] have developed a low-cost nanocomposite such as AC-TiO_2 by a one-step hydrothermal method, which is a potential catalyst for H_2 generation under sunlight. In the photocatalytic H_2 generation process, sacrificial agents have a crucial role in consuming the valence band (VB) holes.

4.5 Environmental applications

TiO_2 is an environmental-friendly material that has been widely used in the photodegradation of a large number of pollutants. Nanostructured TiO_2 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 Cu_2O/TiO_2 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/TiO_2 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 TiO_2 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/TiO_2 nanocomposites against methanol. Píšťková et al. [88] investigated the photodecomposition of acebutolol, propranolol, atenolol, nadolol, and metoprolol, which are β-blockers, using immobilized TiO_2 in an aqueous media. Their results showed a complete photodegradation in 2 h of all tested β-blockers. Coronado et al. [89] described some TiO_2 applications in water purification. This application is argued by the excellent optical and catalytic properties of nanostructured TiO_2, 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 TiO_2 thins films (P/Ag/Ag_2O/Ag_3PO_4) 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. TiO_2 nanostructures are one of the most plentiful nanomaterials having a broad spectrum of applications in nanomedicine. TiO_2 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

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can be explored based on TiO_2 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 TiO_2 nanostructures. Therefore, future studies focused on long-term, constant photoactivity are greatly needed. These can be achieved by changing the synthesis route. Nonmetal-doped TiO_2 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 TiO_2 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-TiO_2). Moreover, Titanium dioxide nanoparticles have gained a lot of attention because of their numerous applications. The formation of TiO_2 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 TiO_2 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.

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