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Review

A critical review on the recent trends of photocatalytic, antibacterial, antioxidant and nanohybrid applications of anatase and rutile TiO2 nanoparticles

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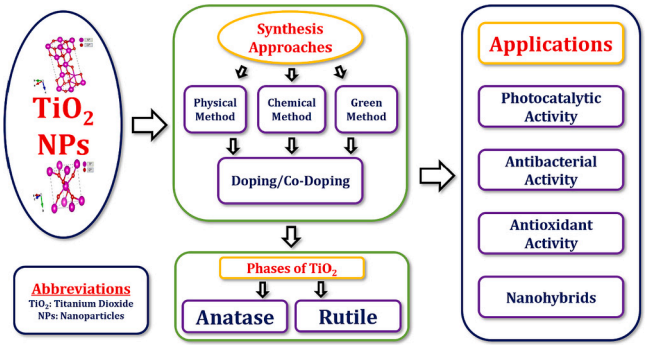
HIGHLIGHTS

- Applications of TiO_2 NPs in photocatalysis, antibacterial, antioxidant, and nanohybrid activities.
- Environmentally friendly synthesis methods (doping and co-doping).
- Influence of size, shape, dose, and exposure time on the synthesized TiO2 NPs.

GRAPHICAL ABSTRACT



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ABSTRACT

Titanium dioxide nanoparticles (TiO_2 NPs) have become a focal point of research due to their widespread daily use and diverse synthesis methods, including physical, chemical, and environmentally sustainable approaches. These nanoparticles possess unique attributes such as size, shape, and surface functionality, making them particularly intriguing for applications in the biomedical field. The continuous exploration of TiO_2 NPs is driven by the quest to enhance their multifunctionality, aiming to create next-generation products with superior performance. Recent research efforts have specifically focused on understanding the anatase and rutile phases of TiO_2 NPs and evaluating their potential in various domains, including photocatalytic processes, antibacterial properties, antioxidant effects, and nanohybrid applications. The hypothesis guiding this research is that by exploring different synthesis methods, particularly chemical and environmentally friendly approaches, and

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incorporating doping and co-doping techniques, the properties of TiO_2 NPs can be significantly improved for diverse applications. The study employs a comprehensive approach, investigating the effects of nanoparticle size, shape, dose, and exposure time on performance. The synthesis methods considered encompass both conventional chemical processes and environmentally friendly alternatives, with a focus on how doping and co-doping can enhance the properties of TiO_2 NPs. The research unveils valuable insights into the distinct phases of TiO_2 NPs and their potential across various applications. It sheds light on the improved properties achieved through doping and co-doping, showcasing advancements in photocatalytic processes, antibacterial efficacy, antioxidant capabilities, and nanohybrid applications. The study concludes by emphasizing regulatory aspects and offering suggestions for product enhancement. It provides recommendations for the reliable application of TiO_2 NPs, addressing a comprehensive spectrum of critical aspects in TiO_2 NP research and application. Overall, this research contributes to the evolving landscape of TiO_2 NP utilization, offering valuable insights for the development of innovative and high-performance products.

1. Introduction

Titanium dioxide (TiO2) has long been considered an ideal nanomaterial due to its high stability, cost-effectiveness, and non-toxic nature, making it safe for both the environment and human use. However, this perception is undergoing significant scrutiny as of 2022, with the European Medicines Agency (EMA) challenging the assumed lack of human toxicity. In 2021, regulations were upheld, leading to the withdrawal of TiO_2 as a food ingredient (E171), and the pharmaceutical industry has been directed to seek alternatives to TiO_2, which is commonly used as an excipient in drugs. This regulatory shift is prompted by emerging evidence that questions the previously presumed non-toxic nature of TiO_2, particularly in the context of human consumption. Furthermore, recent studies highlight the genotoxicity of TiO_2 nanoparticles (NPs) when inhaled into the lungs, adding another layer of concern. These findings contribute to a more nuanced and refined understanding of nanoscale entities, prompting a reassessment of the classification of nanoparticles. The evolving regulatory landscape reflects an increased awareness of potential risks associated with TiO_2, necessitating a reevaluation of its applications and a concerted effort to explore safer alternatives in various industries (Andrade et al., 2023; Anu et al., 2018). The classification of NPs primarily encompasses material composition, size, shape, surface functionalization, and their intended applications (Boverhof et al., 2015; Pourmadadi et al., 2023; Anu et al., 2020). Notably, advancements in nanoscience and nanotechnology have given rise to hybrid NPs that blur the boundaries between traditional classifications. This has introduced new complexities and challenges in defining and categorizing nanoparticles effectively. NPs have gained significant prominence in the modern world due to their inherent chemical, physical, and biological characteristics (Balkrishna et al., 2021a; Eshaghi et al., 2023; Balkrishna et al., 2021b). Material-based classification remains a cornerstone in NPs taxonomy. Researchers continue to broaden the array of materials utilized in the synthesis of NPs, contributing to the expanding diversity within the realm of nanomaterials. Metals like gold and silver have been long-standing choices in fields such as catalysis and nanomedicine. Simultaneously, semiconductor quantum dots have gained significance as crucial elements in imaging and display technologies. The recent upswing in bio-nanotechnology has propelled lipid and polymeric nanoparticles into the spotlight, specifically designed for applications in drug delivery and gene therapy (Hasan, 2015; Vasseghian et al., 2023a; Norouzi et al., 2022). NPs encompass particles with dimensions ranging from 1 to 100 nm, comprising a spectrum of materials including metals, metal oxides, carbon, and diverse organic substances. This material diversity underscores the dynamic nature of nanoparticle research, with various materials finding applications across multiple disciplines, reflecting the continual evolution and expansion of nanotechnology (Khatana et al., 2021; Vasseghian et al., 2023b). NPs size-based classification, crucial for their behavior and applications, has witnessed new developments. Subcategories, including ultrafine particles, NPs, and nanoclusters, help researchers distinguish the unique properties of NPs within specific size ranges. The fine-tuning of synthesis techniques has enabled the precise control of particle size, leading to NPs tailored for specific purposes. Shape-based classification has gained prominence due to the profound impact of NPs shape on their properties (Balkrishna et al., 2021b; Tran et al., 2023; Pour et al., 2022). Spherical NPs have long been favored for their simplicity and ease of synthesis. However, other geometric forms, such as rods, wires, and cubes, have demonstrated exceptional properties for applications in catalysis, plasmonics, and drug delivery. Recent research has unveiled novel approaches for shaping NPs with a high degree of precision, offering greater versatility in design and classification. At the nanoscale, it demonstrates distinctive characteristics attributable to its comparatively greater surface area, chemical stability, heightened reactivity, and robust mechanical strength, among other factors (Hassellöv et al., 2008; Anu et al., 2018; Balkrishna et al., 2021b, 2023). Fig. 1 illustrates the diverse shapes and sizes of NPs.

In the realm of nanomaterials, there are various dimensions to consider. Zero-dimensional (0D) nanodots are characterized by a fixed length, width, and height. One-dimensional (1D) materials, like graphene, are defined by a single parameter. Two-dimensional (2D) materials, exemplified by nanotubes, possess dimensions in terms of length and breadth. Finally, three-dimensional (3D) materials, such as gold nanoparticles (NPs), encompass all three parameters: length, breadth, and height (Ealia and Saravanakumar, 2017; Anu et al., 2020; Kumar et al., 2023a). NPs come in a diverse array of sizes and shapes, exhibiting uniform or irregular structures, which can include conical, spiral, flat, hollow core, cylindrical, tubular, spherical, and more (Thakur and Kumar, 2020; Kumar et al., 2023b; Kumar et al., 2023c). Surface functionalization plays a crucial role in the classification of NPs. Attaching functional groups or ligands to NPs surfaces has a significant impact on their behavior. Recent advancements in this field have resulted in the creation of NPs with improved solubility, stability, and reactivity, rendering them more versatile for particular purposes such as targeted drug delivery and environmental remediation (Cho et al., 2013; Kumar et al., 2023d; Sharma et al., 2021a). Furthermore, the classification of NPs increasingly accounts for their intended application contexts. This dichotomy distinguishes between biological and inorganic NPs, with each category optimized for distinct purposes. The growing field of nanomedicine relies on the precise classification of NPs designed for use in drug delivery, imaging, and therapy within biological systems, highlighting the importance of this distinction (Machado et al., 2015; Sharma et al., 2021b; Sharma et al., 2020a). The classification of NPs is in different categories as given below:

- Organic: Organic and polymer-based NPs e.g., Micelles, Liposomes, Dendrimers, etc. (Ijaz et al., 2020)
- Inorganic: Metals and metals oxide- based NPs e.g., Gold, silver, iron, lead copper, titanium oxide, zinc oxide, aluminum oxide, cerium oxide, etc. (Khan and Hossain, 2022; Li et al., 2021)
- Carbon: Carbon-based NPs e.g., Fullerene (C_{60}), carbon nanotube (CNTs), carbon nanofiber, carbon black, graphene (Gr), and carbon onion (Zahoor et al., 2021; Kumar et al., 2016)

Globally, economic development has led to increased generation and accumulation of waste materials and simultaneously impacted the environment. Several researchers and scientists use various approaches/techniques to address the issue. Light energy (electromagnetic radiation) is considered a convenient system for removing contaminants from waste products (Singh et al., 2019; Thakur et al., 2021a; Sharma et al., 2023). Titanium dioxide (TiO2) is measured an ideal nanomaterial because of its higher stabilities and low-cost and its non-toxic environment and human beings. Over the past five decades, extensive research has been dedicated to TiO_2 NPs, reflecting a growing interest in understanding and harnessing developments in this field (Gupta and Tripathi, 2012; Sharma et al., 2020b). This study focuses on the synthesis of TiO_2 NPs using both chemical and green approaches, incorporating doping and co-doping techniques to enhance their efficiency in photocatalytic activity, antioxidant effects, antibacterial studies, and nanohybrids (Thakur and Thakur, 2023). While existing literature often outlines the synthesis and applications of TiO_2, this comprehensive review seeks to critically evaluate the impact and relevance of these classifications across diverse fields, including nanomedicine, materials science, and environmental science. Despite the abundance of research summarizing TiO_2 synthesis and applications, there exists a notable research gap in critically assessing the implications of these classifications in varied disciplines. This study uniquely addresses this gap by delving into the ethical, safety, and regulatory aspects associated with nanoparticle production and use. Moreover, it explores emerging trends and potential future developments in NPs classification, such as the integration of artificial intelligence for automated classification and the design of nanoparticles tailored for specific functionalities in targeted applications. The primary objective of this review is to emphasize the synthesis of TiO_2 encompassing both phases, namely anatase and rutile. This emphasis is crucial as it directly relates to the desired properties for applications in photocatalysis, antimicrobial activities, antioxidant effects, and nanohybrid functionalities. The study aims to provide a comprehensive overview of TiO_2 NPs synthesis approaches and their diverse applications, serving as a foundation for further research exploration. The methodology involves an in-depth examination of chemical and green approaches for TiO_2 NPs synthesis, with a particular focus on doping and co-doping strategies. The review critically assesses the existing classifications in various fields, considering ethical, safety, and regulatory dimensions. Additionally, it explores emerging trends and potential future directions in NPs classification and design. The review offers insights into the synthesis of TiO_2 NPs with both anatase and rutile phases, highlighting their applications in photocatalysis, microbial studies, antioxidant activities, and nanohybrid functionalities. It goes beyond the conventional scope by critically evaluating the broader impact of TiO_2 classifications in different scientific domains. In conclusion, this comprehensive review provides a unique perspective on TiO_2 NP synthesis and applications, addressing the existing research gap. By exploring ethical considerations, safety aspects, and regulatory dimensions, the study adds a layer of depth to the understanding of TiO_2 NPs. The focus on emerging trends and potential future developments underscores the dynamic nature of this field and encourages further exploration into the synthesis and applications of TiO_2 NPs.

2. TiO_2 nanoparticles: from classification to applications

In 1821, the discovery of TiO_2 marked its emergence as one of the most valuable inorganic compounds in industrial applications. TiO_2 is a white, non-flammable, thermally stable, and insoluble substance (Riyas et al., 2002). It ranks as the 9th most abundant element in the Earth's crust, occurring naturally in various rocks and sands. It is typically obtained from leucoxene or ilmenite ores. M.H Klaproth, a German chemist, was credited with the isolation of an elemental form of TiO_2, known as the rutile phase (Gosavi et al., 2013). The transformation of TiO_2 from an amorphous state to either the anatase or rutile phase is dependent on the specific synthesis conditions. These phase changes are influenced by factors such as pressure, temperature, the presence of dopants, particle size, and hydrothermal conditions. TiO_2 is classified as a Group 4 element on the periodic table and possesses four valence properties.

Additionally, it shows di (TiO) and trivalent (Ti_2O_3) valence states (Roy et al., 2011). TiO_2 is also known as titania and it is mostly utilized as white pigment material for its higher refractive index and brightness. Titania acts as semiconducting materials due to its stable pH range, chemical inertness, non-toxic and band edge deposition (Li et al., 1994; Thakur et al., 2021b). The crystalline state of TiO_2 powder has a growing interest in novel applications in medical science. The application of TiO_2 does not depend upon its properties only but also depends upon the state

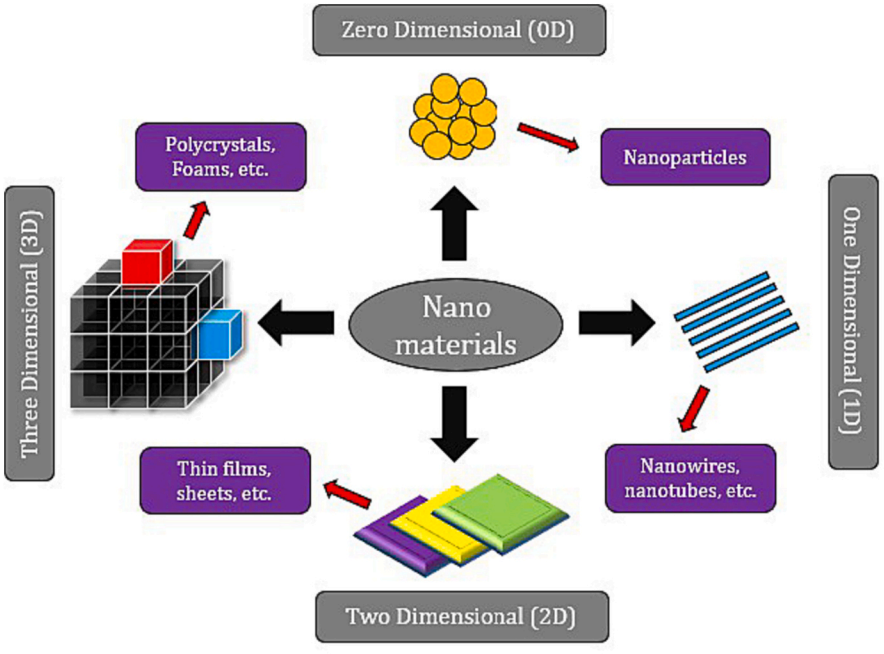

Fig. 1. Different dimensions of nanomaterials.

of TiO_2, either crystalline or amorphous form (Yangi and Wu, 2012; Chen et al., 2006; Thakur et al., 2023a). Some characteristics of TiO_2 are given below (Gomes et al., 2019):

- Amphoteric nature
- Does not dissolve in water as well in acids
- It has high resistivity at room temperature
- It has a boiling point of 3000 °C and a melting point of 1610 °C
- Paramagnetic susceptibility depends upon the temperature

TiO_2 NPs comes with amorphous and crystalline material with three phases: Anatase, Rutile and Brookite. It is classified based on physical features such as optical band gap, surface area and so on (Keskin et al., 2020; Sanjines et al., 1994). The anatase and rutile show tetragonal structure that acts as photocatalysts (Gonzalez et al., 1997; Thakur et al., 2021a). In the TiO_2 crystalline form, the Ti^{4+} ion is encircled by the octahedron oxide ions. In anatase phase, each octahedron ions is commerce with an eight neighbour octahedrons (four oxygen pairs at edge and four oxygen atoms that share a corner) and in rutile structure, each octahedron is connected with ten neighbour octahedrons (two edges and eight corner-sharing) (Murakami et al., 2007; Braun et al., 1992) as shown in Fig. 2 and Fig. 3 respectively (Dambournet et al., 2010; Thakur et al., 2023a, 2023b, 2023c, 2023d, 2023e, 2023f; Thakur et al., 2022a). The anatase and rutile structure explained by the TiO_6 octahedron chain in which six octahedron O^{2-} ions cover each Ti^{4+} ion. The variance in the structure of anatase and rutile is the octahedron chain assembly pattern and distortion of each octahedron (Burdett, 1985; Burdett et al., 1987; Thakur et al., 2023b). In rutile structure, the octahedron is not in a regular arrangement, which shows small minor orthorhombic distortion, whereas, in the case of anatase structure, its regularity is lesser than orthorhombic. The distance between Ti—Ti (3.79 A° and 3.04 A°) and Ti—O (1.934 A° and 1.980 A°) in the anatase phase is larger than the distance between Ti—Ti (3.57 A° and 2.96 A°) and Ti—O (1.949 A° and 1.980 A°) in the rutile phase (Winkler, 2014). Table 1 shows a comparison of the two categorization modes of TiO_2: anatase and rutile (Wang et al., 2014; Yaghoubi et al., 2010; Ming et al., 2011; Tian et al., 2003).

The alignment of TiO_2 NPs is alienated in three main classes within a 1–100 nm size range: (i) spherical like spheres (Zeng et al., 2011; Karuppuchamy and Jeong, 2005), (ii) elongated like nanorods (Yemmireddy et al., 2015; Mu et al., 2008; Lucky et al., 2015) and (iii) planar like nanoplates (Chatterjee et al., 2008; Chinen et al., 2015; Schneider et al., 2014). Spherical based TiO_2 NPs show various applications such as electronics, photodynamic therapy, sensors, catalysis and antimicrobial (Kubacka et al., 2014; Vargas and Rodríguez-Páez, 2017; Marwaha et al., 2017, Todescato et al., 2016; Fischer et al., 2015; Chen et al., 2016). Elongated TiO_2 NPs reveal numerous probable applications such as display technologies, microelectromechanical systems (MEMS), cancer therapeutics, imaging and drug delivery (Yao et al., 2014; Kang et al., 2012; Nine et al., 2015; Verma et al., 2017; Yavuz et al., 2016). Anti-corrosives, bacterial, reflection, graffiti coatings, wound treatment, and tissue engineering are all applications for planar TiO_2 NPs. (Jiang et al., 2015; Park et al., n.d.; Shin et al., 2016; Kumar et al., 2016). Some properties and applications of TiO_2 NPs are listed in Table 2. The several phases used in the synthesis of TiO_2 NPs reported by various researchers are listed in Table 3.

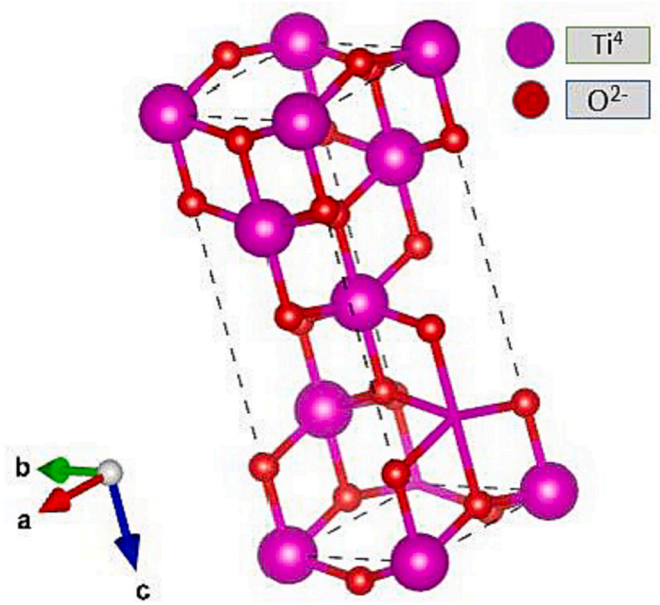

Fig. 2. Crystal structure of anatase TiO_2.

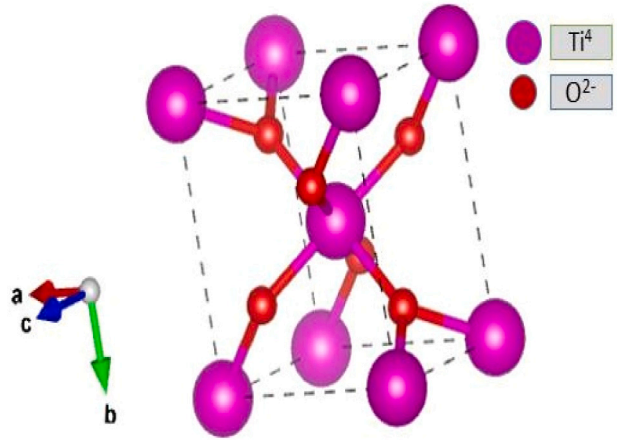

Fig. 3. Crystal structure of rutile TiO2.

Table 1
Comparable study on classifications of TiO2 (Wang et al., 2014; Yaghoubi et al., 2010; Ming et al., 2011; Tian et al., 2003).

	Anatase	Rutile
Formula weight	79.890	79.890
Z	4	2
Crystal structure	Tetragonal	Tetragonal
Space group	I41/amd	P42mnm
Point group	4/m2/m2/m	4/m2/m2/m
Unit cell a(A°) b(A°) c(A°)	3.7842–9.5146	4.5845–2.9533
Molar volume (cm^3/mol)	20.156	18.693
The volume of the elementary cell (nm^3)	136.25	62.07
Melting point (°C)	Transformation to rutile	1830–1850
Density (g/cc)	3.895	4.2743
Major application	Photocatalytic	White paint

Table 2
Properties and applications of anatase and rutile TiO_2 NPs.

S. No.	Phase of TiO2	Properties	Applications
1.	Anatase TiO_2	Metastable polymorph, lustrous, hard, high density, low absorption rate, more significant bandgap	Paints, papers, ceramics, gems, photocatalysis, antimicrobial, antioxidant
2.	Rutile TiO_2	High chemical resistance, refractive index, hard, UV absorbent, formed at high temperature	Plastic, papers, paints, food, sunscreens, photocatalysis, antioxidant, antimicrobial

Table 3
TiO_2 NPs with various phases.

Compound	Phase	References
TiO_2	Anatase	(Shin et al., 2010; Limmer et al., 2004; Nishikiori et al., 2007; Wu et al., 2019; Liu et al., 2020)
	Rutile	(Fujishima and Honda, 1972; Gervais et al., 2001; Hu et al., 2003; Wang et al., 2008; Othman et al., 2011; Xiang et al., 2012)
	Anatase and Rutile	(Li et al., 2002; Lee et al., 2014; Attar et al., 2008; Mozia, 2010; Eslami et al., 2016; Haider et al., 2017; Goutam et al., 2018)

3. Synthesis of TiO_2

The transition from 0D to 3D nanostructures requires the essential utilization of synthetically designed TiO_2 NPs. By precisely regulating the shape and size of TiO_2 NPs, a wealth of unique attributes and applications unfolds, especially in the realm of biological sciences (Chen and Selloni, 2014; Thakur et al., 2022b; Thakur et al., 2023a, 2023b, 2023c, 2023d, 2023e, 2023f). The controlled manipulation of size and shape grants TiO_2 NPs the remarkable ability to transition seamlessly from dimensions spanning from nanometers down to the molecular scale, and from spherical forms to diverse morphologies like nanorods, nanotubes, and nanowires. This level of control over TiO_2 NPs' morphological characteristics is particularly captivating, as it holds promise for a wide array of technical and biosafety applications (Longoni et al., 2017; Potapenko et al., 2015; Zhao et al., 2010; Thakur et al., 2021a, 2021b, 2021c). Fig. 4 visually presents the various methodologies and techniques employed in the fabrication of TiO_2 nanoparticles, illustrating the multifaceted approaches used in their synthesis.

There are two fundamental approaches when it comes to the synthesis of nanostructures: the top-down approach and the bottom-up approach, each offering unique advantages and applications.

- Top-Down Approach: This technique involves the reduction in size of larger structures to create smaller ones. In this method, small structures are fabricated from larger ones. An illustrative example of the top-down approach is the manufacturing of integrated circuits, where the circuitry is constructed layer by layer, reducing the size at each step. Once this process is complete, no further action is required (Wang and Xia, 2004; Gazit, 2007).
- Bottom-Up Approach: In contrast, the bottom-up approach involves building complex nanostructures by systematically assembling molecular precursors. This method allows for the creation of intricate and well-defined nanostructures. There are four major branches within the bottom-up approach, which are physical, chemical, hybrid, and biological methods. These methods are designed to provide a systematic and controlled means of forming nanostructures (Wan et al., 2007).
- Physical Approaches: Physical methods in the bottom-up approach rely on physical processes, such as deposition and self-assembly, to create nanostructures.
- Chemical Approaches: Chemical methods utilize chemical reactions to build nanostructures. These can include processes like sol-gel synthesis and chemical vapor deposition.
- Hybrid Approaches: Hybrid methods combine both physical and chemical techniques to construct nanostructures, often achieving enhanced control and properties.
- Biological Approaches: Biological methods leverage biological entities, such as proteins or organisms, to facilitate the controlled formation of nanostructures.

It is worth emphasizing that current biological, hybrid, and chemical synthesis methods may incorporate organic or hazardous chemicals and necessitate intricate reaction conditions for the production of desired compounds. This often leads to constraints in both the quantity and quality of the final products (Cai et al., 2003; Colvin, 2003; Thakur et al., 2022c; Thakur et al., 2023c). As a result, the technical challenge has led to the exploration of chemical routes for the integration of TiO_2 nanoparticles. These chemical methods enable precise control over the long-term performance of TiO2 nanoparticles and find applications in a variety of technical and security-related fields (Lee et al., 2010; Rao et al., 2007).

The production of TiO_2, along with NPs, involves several stages in the chemical process. Hydrothermal and sol-gel synthesis methods have traditionally been popular, but microwave-assisted and green chemistry techniques are gaining increased popularity (Dambournet et al., 2010; Burdett, 1985; Burdett et al., 1987; Winkler, 2014; Thakur et al., 2023d). By carefully designing and adjusting various parameters of the process, such as the choice of substrates, solvent ratios, temperature, and duration, it is feasible to create materials with specific physicochemical properties. These properties encompass surface area, NPs morphology and structure, NPs size and size distribution uniformity, NPs crystallinity

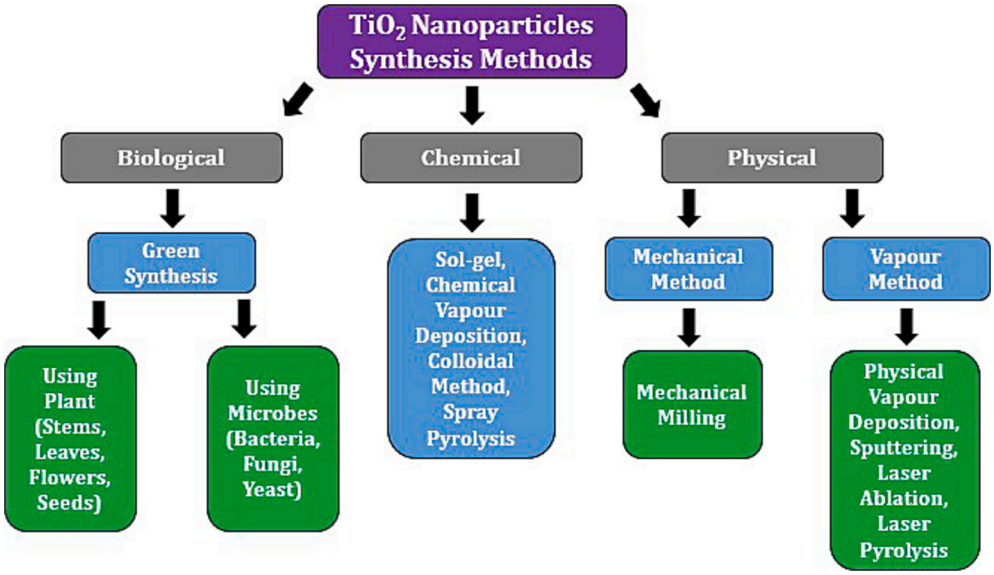

Fig. 4. Different synthesis methods of TiO_2 nanoparticles.

and crystal phase, NPs photoactivity, and more. Additionally, these characteristics can be altered after synthesis through methods like doping, surface functionalization, organic molecule binding, or by introducing various surfactants or dopants during NPs synthesis (Braun et al., 1992; Burdett, 1985; Thakur et al., 2023d). A range of surfactants or dopants, as well as post- synthetic changes such doping, surface functionalization, and organic molecule binding, can alter the TiO2 particles. The normal continuous pad dry cure procedure for applying various finishing agents is not suitable for surface modification of TiO2 NPs, because TiO2 NPs require longer contact durations due to their generally low adherence. As a result, the most frequent application method is to immerse the substrate in TiO2 sol for an adequate duration of time under proper circumstances, then dry with or without squeezing.

3.1. Chemical approach

Sol-gel, hydrothermal, and co-precipitation methods for chemically creating TiO2 NPs provide a number of benefits (Tok et al., 2006), including:

- structural and stoichiometry categories are under control
- size, morphology and similarity
- ideal for large-scale manufacturing, low cost, and high purity of NPs
- quick reaction circumstances and less expensive actions

The different researchers who have worked and synthesized TiO_2 NPs by chemical approach are listed in Table 4.

3.2. Green approach

The utilization of green techniques in NPs synthesis offers distinct advantages, primarily stemming from the significantly increased surface area per unit volume compared to bulk materials of the same composition. These methods yield NPs with unique chemical and physical properties, making them highly versatile for a wide range of applications, including catalysis, drug delivery, anticancer treatments, and antibacterial agents (Nadaroglu et al., 2017; Herlekar et al., 2014). The green approach to NPs synthesis leverages naturally occurring biological components such as sugars, fungi, bacteria, and plants, as well as biodegradable materials (Swierczewska et al., 2011). This approach is characterized by its simplicity and environmental friendliness, as it minimizes the use of harmful chemicals, operates under low pressure and temperature conditions, and does not rely on synthetic materials for the creation of green NPs (Alexandridis, 2011). Innovative applications often require the precise control of NPs morphology, encompassing both shape and size. The ability to engineer nanoparticles with diverse morphologies, such as nanorods, nanospheres, nanoporous structures, and nanowires, is of paramount importance in achieving desired performance characteristics (Das et al., 2017; Gahlawat and Choudhury, 2019). Table 5 lists various researchers who have actively contributed to the synthesis of TiO_2 NPs using green approaches, underscoring the importance and growing interest in this environmentally friendly and versatile nanoparticle synthesis method.

3.3. Mechanism of TiO_2 NPs synthesis

In an aqueous or non-aqueous solution of a Ti precursor, a reducing agent is dissolved to produce TiO_2 NPs (Arvizo et al., 2010). The existence of a stabilizing factor that influences the aggregation of clusters

Table 5
Synthesis of TiO_2 NPs by green approaches.

S. No.	Method	Precursor + Plant	Compound	Size (nm)	References
1.	Green approach	Titanium tetrachloride + *Cicer arietinum* L.	Anatase	14	(Nadeem et al., 2018)
2.	Green approach	TiO2 powder + M. communis L	Anatase	17–25	(Nasrollahzadeh and Sajadi, 2016)
3.	Green approach	Titanium (iv) isopropoxide + *Aloe vera*	Anatase	60–80	(Khadar et al., 2016)
4.	Green approach	Titanium (iv) isopropoxide + *Cynodon dactylon*	Anatase	13–34	(Zhu et al., 2019)
5.	Green approach	Titanium (iv) isopropoxide + *Moringa oleifera*	Anatase	12	(Patidar and Jain, 2017)
6.	Green approach	Titanium oxy sulphate + Trigonella foenum	Rutile	20–90	(Subhapriya and Gomathipriya, 2018)
7.	Green approach	Titanium tetrachloride + Orange peel	Anatase	20–50	(Amanulla and Sundaram, 2019)
8.	Green approach	Titanium trichloride + Cucurbita pepo	Anatase	20–50	(Abisharani et al., 2019)
9.	Green approach	Titanium (iv) isopropoxide + *Aloe vera*	Anatase	11	(Hariharan et al., 2019)
10.	Green approach	Titanium (iv) isopropoxide + *Mentha arvensis*	Anatase	20–70	(Ahmad et al., 2020)
11.	Green approach	TiO2 + Lemon peel	Anatase	500–800	(Nabi et al., 2020)

Table 4
Synthesis of TiO_2 NPs by chemical approaches.

S.No.	Method	Precursor	Compound	Size (nm)	References
1.	Hydrothermal	Tetrabutyl titanate	Anatase	20–100	(Liu et al., 2015)
2.	Chemical surface Treatment	TiO2 powder	Anatase	22–31	(Qin et al., 2015)
3.	Sol-gel	Titanium (iv) isopropoxide	Anatase	9–13	(Tahir and Amin, 2015)
4.	Hydrothermal	Tetrabutyl	Anatase	10–20	(Sood et al., 2015)
5.	Sol-gel	Titanium (iv) isopropoxide	Anatase	11–15	(Al-Taweel and Saud, 2016)
6.	Precipitation	Titanium (iv) isopropoxide	Anatase	15	(Ali et al., 2016)
7.	Sol-gel	Titanium (iv) isopropoxide	Anatase	11–24	(Sahu, 2016)
8.	Sol-gel	Titanium (iv) isopropoxide	Anatase	30–40	(Lusvardi et al., 2017)
9.	Sol-gel	Titanium (iv) isopropoxide	Anatase	20–30	(Askari et al., 2017)
10.	Solvothermal	Titanium (iv) isopropoxide	Anatase	5	(Ramakrishnan et al., 2018)
11.	Hydrothermal	Tetrabutyl titanate	Anatase	30–40	(Zhang et al., 2018a, 2018b)
12.	Precipitation	Titanium (iv) isopropoxide	Anatase and rutile	11–28	(Buraso et al., 2018)
13.	Precipitation	Titanium tetrachloride	Anatase	5–7	(Hariharan et al., 2019)

and NPs is conceded throughout the entire process (Makarov et al., n.d.). A repulsive force, such as steric stabilisation or electrostatic stabilisation, is produced when the stabilizing component is absorbed onto the surface of Ti NP and displace the aggregation (Chanda et al., 2011). According to the chemical process, the three phases of the TiO_2 NPs synthesis are Ti atom nucleation, precipitation and crystal nuclei growth (Sathishkumar et al., 2009). In the first phase, Ti atom nucleation, precursor compounds containing Ti undergo a nucleation process where individual Ti atoms cluster together to form small, primary particles. This marks the initiation of NPs formation. The nucleation phase is crucial as it sets the foundation for the subsequent steps in the synthesis (Qamar et al., 2023). Following nucleation, the process enters the precipitation phase. During this stage, the nucleated particles continue to grow in size as additional Ti atoms are deposited onto the existing clusters. This results in the formation of larger, intermediate particles. The conditions during precipitation, such as temperature, pressure, and the concentration of reactants, play a significant role in determining the size and morphology of the NPs (Vembu et al., 2022). The final phase is crystal nuclei growth, wherein the intermediate particles further mature into well-defined crystalline structures. This phase involves the continued deposition of Ti atoms onto the growing particles, leading to the development of distinct crystal facets and the ultimate formation of TiO_2 NPs with specific sizes and shapes (Younis et al., 2023). These three phases collectively govern the synthesis of TiO_2 NPs, and controlling the parameters at each stage is crucial for tailoring the properties of the nanoparticles for various applications, including catalysis, sensing, and photocatalysis (Li et al., 2023). Reducing agents and stabilizing factors play crucial roles in the synthesis and stability of nanoparticles, including TiO_2 NPs. Various types of reducing agents and stabilizing factors are employed in NPs synthesis to control size, shape, and prevent aggregation (Sagadevan et al., 2022). In chemical synthesis, common reducing agents include organic compounds such as citrate, hydrazine, and ethylene glycol, which facilitate the reduction of metal precursors to form NPs. These reducing agents contribute to the control of nucleation and growth processes, influencing the final characteristics of TiO_2 NPs (Joshi et al., 2022). Stabilizing factors, often surfactants or polymers, are employed to prevent agglomeration and enhance colloidal stability. Surfactants like cetyltrimethylammonium bromide (CTAB) and polyvinylpyrrolidone (PVP) form a protective layer around the NPs, preventing uncontrolled growth and maintaining particle dispersion (Gan et al., 2022). The choice of reducing agents and stabilizing factors is crucial in tailoring the properties of TiO_2 NPs, influencing their performance in various applications such as photocatalysis, antimicrobial activities, and nanohybrids. Understanding and optimizing these factors contribute significantly to the reproducibility and functionality of TiO_2 NPs in diverse contexts (Al-Mamun et al., 2022). Reducing agents is combined to Ti atom precursors solution during the first phase, known as precipitation. While the Ti atom concentration is steadily rising, the precursor is diminished (Swierczewska et al., 2011). Crystal nuclei begin to form when the concentration of Ti atoms in the second phase (Nucleation) exceeds the crucial supersaturation point. With crystal formation and growing nuclei, the Ti atom concentration begins to decrease (Alexandridis, 2011). A considerable amount of Ti atoms is consumed during the third phase (growth of crystal nuclei). Nuclei development controls the entire process as the concentration of Ti steadily declines below the crucial supersaturation point (Das et al., 2017). The formation of crystal nuclei is stopped when the concentration falls below the saturation threshold, and pure TiO_2 NPs are then created (Gahlawat and Choudhury, 2019; Polte et al., 2010a). The quantity and homogeneity of TiO2 NPs are significantly impacted by the mixing of the precursor and reducing agent during the first and second stages of the mechanism (Polte et al., 2010b; Xia et al., 2009).

3.4. Doping and co-doping

3.4.1. Role of dopants

Doping, or the intentional introduction of foreign elements into metallic oxides, is a common strategy used to enhance their optical, electrical, and catalytic properties (Garcia et al., 2011). The primary mechanism behind these property enhancements involves the controlled manipulation of doping, as illustrated in Fig. 5, which brings about alterations in the crystalline structure (Buonsanti and Milliron, 2013). These structural changes, in turn, lead to the narrowing of the bandgap and a shift in the energy conduction band's position. When metallic oxides like the widely used photocatalyst TiO_2 are doped with non-metals, transition metals, or noble metals, the bandgap of the material is effectively reduced (Pelaez et al., 2012a, 2012b). This reduction in bandgap, induced by doping, transforms TiO_2 from being solely photoactive in the UV range to becoming photocatalytic under visible light. This is a highly significant development, as it enables TiO_2 to produce reactive oxygen species (ROS) when exposed to visible light. Moreover, the alterations to the material's properties, either by modifying the lattice structure or introducing dopants that act as electron traps, serve to prevent charge recombination. This means that the recombination of photoexcited electrons and holes is minimized, and the introduction of an intermediate energy level between the conduction and valence bands facilitates more efficient charge separation and utilization in photocatalysis and other applications. This, in essence, enhances the overall efficiency and effectiveness of the doped metallic oxides.

The introduction of dopants often leads to disruptions in the lattice structure of the parent metal oxides, resulting in doping-induced alterations at the conduction band edge. This perturbation in the electrical structure is irreversible and leads to changes in electron concentrations within the conduction band (Schimpf et al., 2015). The extent of these changes is influenced by factors such as the quantity of dopants and their distribution throughout the material. The process of doping, or the incorporation of foreign elements into TiO_2, represents a significant advancement in altering the physical properties of this material. The primary objective of doping is to narrow the bandgap, thereby enabling the absorption of visible light. Photocatalytic systems featuring doped catalysts exhibit enhanced performance (Carp et al., 2004). Ideally, when doping TiO_2 NPs, maintaining the crystal structure while altering the electrical composition is preferable. It is generally easier to introduce Ti^{4+} ions into TiO_2 as cations than to replace O^{2-} ions with other anions, owing to differences in charge states and ionic radii (Mor et al., 2006). Furthermore, surface modification of TiO_2 NPs offers advantages superior to bulk TiO_2 alteration (Burda et al., 2003). This approach allows for more precise control over the material's properties and its interaction with its surroundings. Table 6 provides a list of various researchers who have actively contributed to the synthesis of doped and co-doped TiO_2 NPs, highlighting the growing interest in this field and its potential applications.

4. Applications

4.1. Photocatalytic activity

In 1972, Fujishima and Honda made a groundbreaking discovery by introducing photocatalytic water splitting using TiO_2 as electrodes, marking the inception of the era of heterogeneous photocatalysis (Senanayake, 2013). The concept of photocatalysis involves utilizing light to activate a catalyst, thereby accelerating a chemical reaction by lowering the activation energy (Xiao et al., 2015; Sharma et al., 2020a). TiO_2 is particularly well-suited for photocatalytic reactions designed to eliminate inorganic or organic pollutants in air or water due to its relatively wide bandgap (Gribb and Banfield, 1997). It offers several crucial advantages, such as a high oxidation rate, non-toxicity, low cost, and chemical stability compared to other metal oxides (Kumbhar, 1993; Castillo et al., 1995; Sharma et al., 2020b). Achieving a higher surface

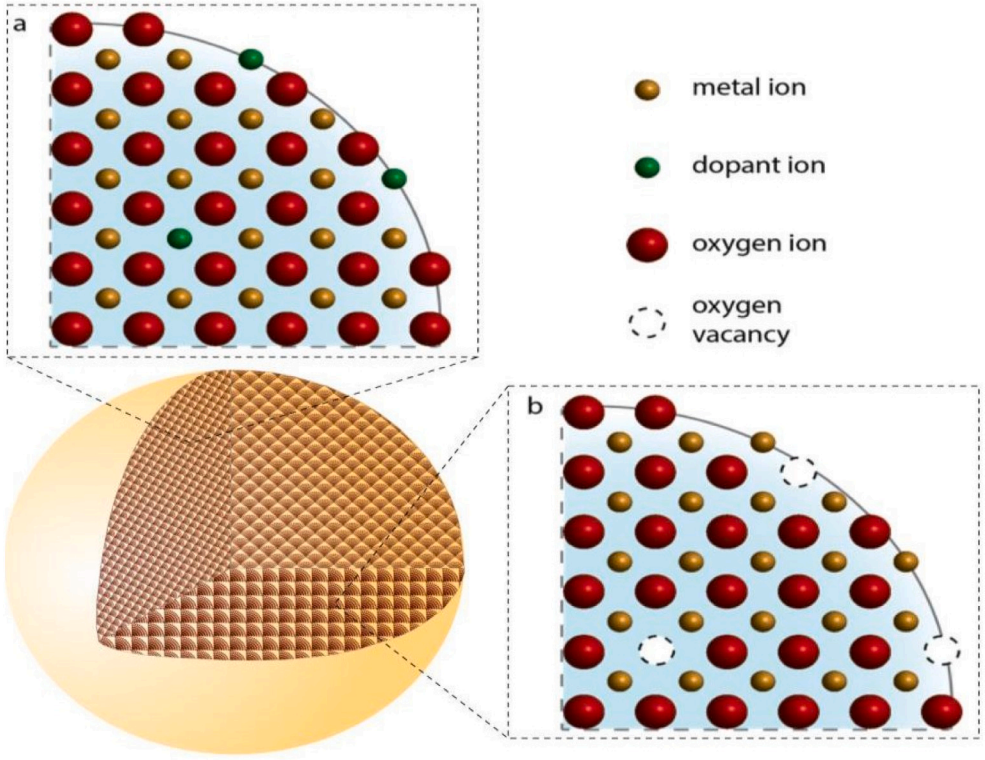

Fig. 5. Scheme diagram of (a) dopants ion and (b) defect or vacancy in crystal phase, Reprinted with permission from Elsevier (License No.: 5239300891673) (Saleh et al., 2016).

Table 6
Synthesis of doped and co-doped TiO_2 NPs.

S. No.	Phase	Method	Doping/Co -doping	Dopants elements	Applications	References
1.	Anatase	Sol-gel	Doping	Copper (Cu)	Photocatalytic	Yang et al., 2015
2.	Anatase and Rutile	Sol-gel	Doping	Cobalt (Co)	–	Mugundan et al., 2015
3.	Anatase	Sol-gel	Doping	Silver (Ag)	Antibacterial	Bahadur et al., 2016
4.	Anatase	Sol-gel	Doping	Copper (Cu)	Photocatalytic	Krishnakumar et al., 2016
5.	Anatase	Sol-gel	Doping	Silver (Ag)	Anticancer	Ahamed et al., 2017
6.	Anatase	Sol-gel	Doping	Iron (Fe)	Photocatalytic	Ali et al., 2017
7.	Anatase	Sol-gel	Doping	Silver (Ag)	Photocatalytic and Antibacterial	Ali et al., 2018
8.	Anatase	Sol-gel	Doping	Manganese (Mn)	Photocatalytic and Antibacterial	Zahid et al., 2018
9.	Anatase	Sol-gel	Doping	Gadolinium (Gd)	Photocatalytic and Antibacterial	Ben Chobba et al., 2019
10.	Anatase	Sol-gel	Doping	Cerium (Ce)	–	Marami and Farahmandjou, 2019
11.	Anatase	Sol-gel	Doping	Carbon (C)	Anticancer	Yang et al., 2020
12.	Anatase	Sol-gel	Doping	Nitrogen (N) and Copper (Cu)	Photocatalytic	Reda et al., 2020
13.	Anatase	Hydrothermal	Co-doping	Carbon-Yttrium (C- Y)	Photocatalytic	Khalid et al., 2015
14.	Anatase	Sol-gel	Co-doping	Silver- Strontium (Ag—Sr)	Photocatalytic	Naraginti et al., 2015
15.	Anatase	Solid phase	Co-doping	Sulphur- Carbon (S-C)	Lithium-ion battery	Ivanov et al., 2016
16.	Anatase	Sol-gel	Co-doping	Tin-Cerium (Sn—Ce)	Photocatalytic	Kaleji et al., 2016
17.	Rutile	Sol-gel	Co-doping	Cobalt-Tin (Co—Sn)	Photocatalytic	Alijani et al., 2017
18.	Anatase	Sol-gel	Co-doping	Vanadium-Lanthanum (V—La)	Photocatalytic	Ilkhechi et al., 2017
19.	Anatase	Sol-gel	Co-doping	Tungsten- Molybdenum (W—Mo)	Photocatalytic	Avilés-García et al., 2018
20.	Anatase	Sol-gel	Co-doping	Manganese- Cobalt (Mn-Co)	Photocatalytic	Sayed et al., 2018
21.	Anatase	Sol-gel	Co-doping	Tin-Iron (Sn—Fe)	Antibacterial	Hosseini et al., 2019
22.	Anatase	Sol-gel	Co-doping	Cerium- Manganese (Ce—Mn)	Photocatalytic	Tbessi et al., 2019
23.	Anatase	Sonochemical	Co-doping	Manganese- Zinc (Mn-Zn)	Photocatalytic	Wattanawikkam and Pecharapa, 2020
24.	Anatase	Sol-gel	Co-doping	Nickle- Lanthanum (Ni—La)	Photocatalytic	Bashir et al., 2020

area of TiO_2 during the synthesis process involves careful control of various parameters, including particle size, crystal phase, lattice defects, and surface morphology (Chen et al., 2011). Achieving a higher surface area of TiO_2 during the synthesis process is a multifaceted task that requires meticulous control of several parameters. The particle size is a critical factor; smaller particles inherently offer a larger surface area-to-

volume ratio. Therefore, precise regulation of nucleation and growth stages is essential to produce fine TiO_2 NPs. The crystal phase of TiO_2 also influences surface area, as different crystal structures exhibit distinct surface energies. The anatase phase, for example, is known to have higher surface energy compared to rutile, contributing to increased surface area. Careful manipulation of synthesis conditions can favor the formation of specific crystal phases (Ur Rehman et al., 2022). Lattice defects, such as vacancies or oxygen vacancies, can enhance surface reactivity and contribute to an augmented surface area (Hu et al., 2023). Moreover, the surface morphology plays a pivotal role. Unique surface features, such as mesopores or nanoscale surface roughness, can significantly amplify the overall surface area. Utilizing templating agents or adjusting reaction parameters can help achieve the desired surface morphology, thereby maximizing the exposed surface area of TiO_2 NPs (Bahramian et al., 2023). In essence, a synergistic control of particle size, crystal phase, lattice defects, and surface morphology is imperative for optimizing the surface area of TiO_2 during synthesis, ensuring enhanced performance in applications like catalysis and photocatalysis (Helmy et al., 2023). The porous nature of TiO_2 enables a high degree of dispersion, resulting in a greater active surface area that enhances its catalytic activity (Yang et al., 2014; Singh et al., 2012). There are different phases of TiO_2, with rutile TiO_2 NPs having an energy band gap of 3.02 eV and anatase TiO_2 NPs having a slightly wider 3.2 eV energy band gap, with an absorption edge at 386 nm within the UV region (Fujishima and Zhang, 2006; Thakur et al., 2021b). When TiO_2 NPs absorb UV light with a wavelength in the range of 280–400 nm, an electron is excited from the valence band to the conduction band, creating an electron-hole pair (Murphy and Strongin, 2009; Schneider et al., 2014; Nozik and Memming, 1996; Berek et al., 2012; Horn et al., 1972). This process is illustrated in Figs. 6 and 7. This excitation of electrons and the creation of electron-hole pairs in TiO_2 NPs serve as the fundamental driving force for various photocatalytic reactions, where these charged species can participate in redox reactions to break down and degrade organic and inorganic contaminants in the presence of the catalyst and UV light. This property makes TiO_2 a crucial material for environmental remediation and other photocatalytic applications.

$$TiO_2 + h\nu \rightarrow e- + h^+$$

The photocatalytic activity of TiO_2 is primarily attributed to its ability to generate electron-hole pairs upon exposure to light, typically ultraviolet (UV) radiation. This process involves the excitation of electrons from the valence band to the conduction band, creating electron-hole pairs. These photoinduced electron-hole pairs play a crucial role in the degradation of various contaminants through specific mechanisms (Alhaddad et al., 2022). In photocatalytic reactions, the generated electron-hole pairs participate in redox reactions with adsorbed species on the TiO_2 surface. The electrons in the conduction band act as reducing agents, while the holes in the valence band act as oxidizing agents. For example, in the degradation of organic pollutants, the photogenerated electrons can reduce oxygen molecules to form superoxide radicals ($O_2^{\bullet -}$), and the holes can oxidize water molecules to produce hydroxyl radicals ($^{\bullet}OH$). These highly reactive radicals then initiate a series of oxidation-reduction reactions, leading to the degradation of organic contaminants (Kong et al., 2022). Additionally, the photocatalytic activity of TiO_2 can be enhanced by doping it with certain elements. For instance, nitrogen-doped TiO_2 can extend the light absorption range into the visible region, promoting the generation of electron-hole pairs under visible light. This expands the application of TiO_2 photocatalysis to scenarios with lower energy UV or visible light sources (Maqbool et al., 2022). Furthermore, TiO_2's surface properties, including defects and active sites, play a crucial role in facilitating the adsorption of contaminants and promoting the efficiency of photocatalytic reactions. The electron-hole pairs generated on TiO_2 surface can directly react with adsorbed contaminants, leading to their mineralization into harmless byproducts, such as water and carbon dioxide (Alhalili and Smiri, 2022). In summary, TiO_2's photocatalytic degradation of contaminants involves the generation of electron-hole pairs under light exposure, redox reactions with adsorbed species, and the formation of reactive radicals that initiate the degradation processes. Doping and surface modifications further enhance TiO_2's photocatalytic capabilities, making it a promising material for environmental remediation applications (Khan et al., 2022). Table 7 lists the various scientists who have created TiO_2 NPs and their respective photocatalytic activity. One challenge lies in optimizing the photocatalytic efficiency of TiO_2, particularly under visible light, where its performance traditionally lags. Enhancing visible light absorption and reducing electron-hole recombination rates are ongoing focal points for researchers. Another challenge involves the potential toxicity of TiO_2 NPs, necessitating a thorough understanding of their environmental and biological impacts. Effective strategies for mitigating toxicity, such as surface modifications and controlled synthesis, need to be developed to ensure safe and sustainable applications. The future scope of TiO_2 NPs in photocatalysis involves advancing their versatility and expanding applications beyond environmental remediation to include energy conversion and biomedical fields. Tailoring the properties of TiO_2, exploring novel hybrid materials, and integrating advanced characterization techniques will contribute to harnessing their full potential. Additionally, exploring scalable and cost-effective synthesis methods will be pivotal for widespread implementation. TiO_2 NPs hold immense potential in photocatalysis, addressing challenges like limited visible light responsiveness and toxicity concerns is crucial. The future trajectory involves refining their properties, expanding applications, and ensuring environmental and biological safety for sustainable and diverse utilization.

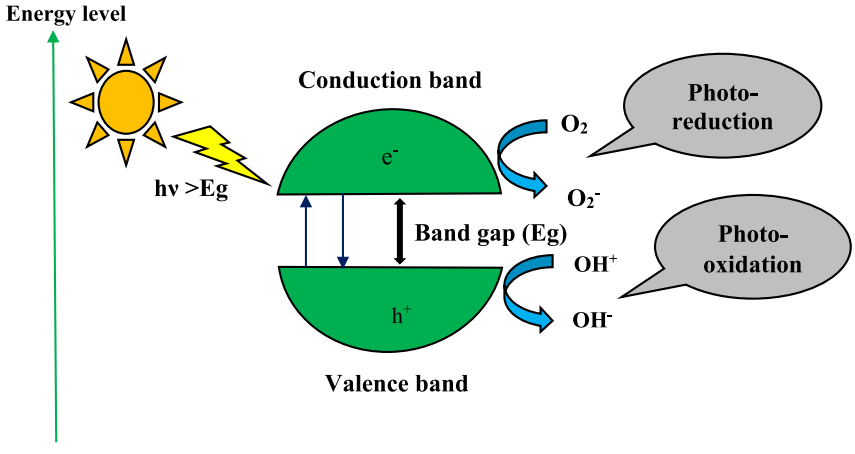

Fig. 6. Photocatalytic process of TiO_2.

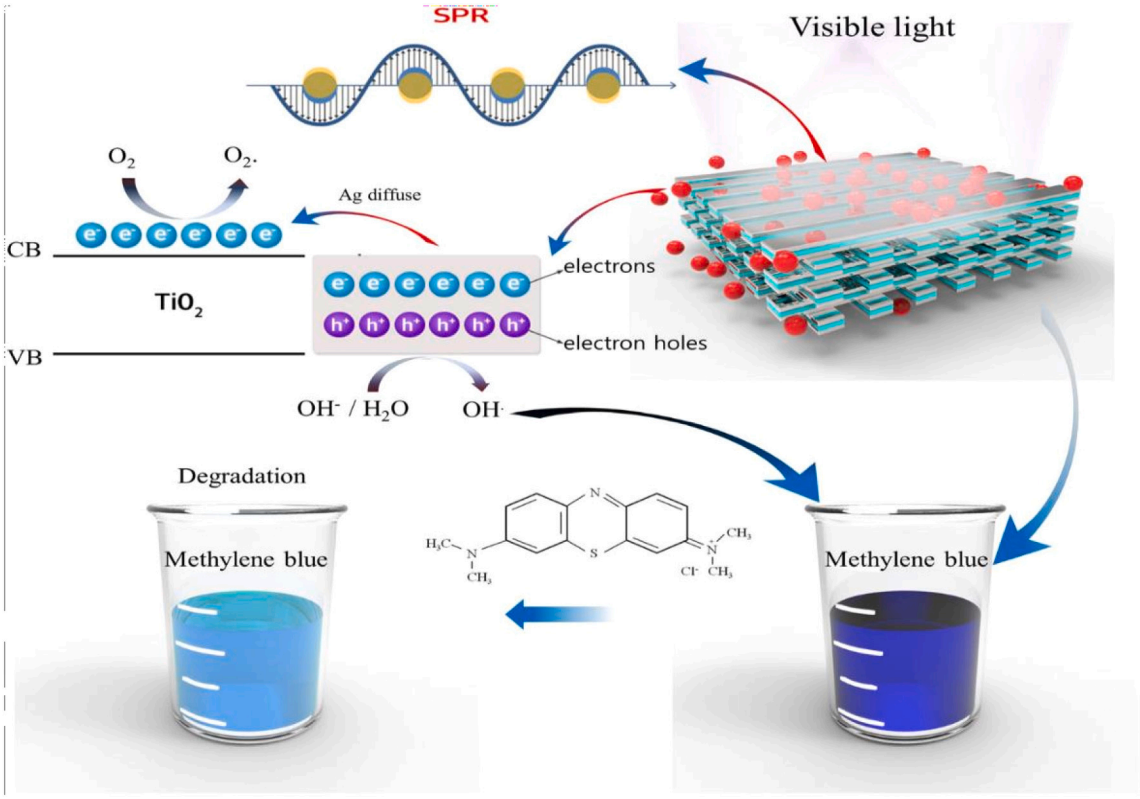

Fig. 7. Mechanism of photodegradation of dye by TiO_2 NPs (Copyright © 2021 by the authors. Licensee Springer Nature, Berlin, Germany) (Zhao et al., 2017).

4.2. Antibacterial study

The antibacterial activity of NPs is profoundly influenced by various internal characteristics, including morphology, size, chemistry, source, and nanostructure (De Oliveira et al., 2017; Pal et al., 2007; Chenot et al., 2019; Lopez de Dicastillo et al., 2018). For TiO_2 NPs, their antibacterial activity is intrinsically tied to their photocatalytic properties, which, in turn, depend significantly on their morphological, structural, and textural attributes (He et al., 2013). The physicochemical and antibacterial characteristics of TiO_2 NPs are shaped by factors such as their crystal shapes and content (Burda et al., 2005). Extensive research has been conducted on TiO_2-based NPs with bactericidal properties due to their exceptional photocatalytic activity (Pelaez et al., 2012a, 2012b; Zhukova, 2015; Hajipour et al., 2012; Akhavan, 2009). It has been demonstrated that TiO_2 NPs, when exposed to UV light irradiation, exhibit toxic effects on both gram-negative and gram-positive bacteria (Kim et al., 2018; Yeh et al., 2013; Zhang et al., 2013). Under UV light exposure, TiO_2 NPs generate holes and electron vacancies in their valence and conduction bands, as indicated by numerous studies (Shieh et al., 2006). These holes and electrons are present in an oxygen-rich aqueous environment, displaying strong oxidizing properties that target bacteria by damaging their cell walls and cellular components (Jang et al., 2001; Nithya et al., 2018). Furthermore, the efficacy of TiO_2 NPs against bacteria when exposed to UV radiation is influenced by the interactions between the NPs and the bacteria (Feris et al., 2010). TiO_2 NPs are generally unable to inhibit bacteria under UV light irradiation in the absence of the development of large aggregates (Planchon et al., 2013). After UV light treatment for varying durations, the bacteria within the TiO_2 compound tend to become inactive initially, with cell density increasing as treatment time progresses, while other components ultimately become devoid of viable cells (Zhukova et al., 2012; Zhukova et al., 2010; Joost et al., 2015). This complex interplay between TiO_2 NPs, UV radiation, and bacteria underscores the importance of understanding and tailoring the internal characteristics of NPs for optimal antibacterial activity.

The mechanisms of action of NPs against various bacterial pathogens play a pivotal role in understanding their diverse applications. It has been observed that NPs often face higher resistance in gram-positive bacteria, highlighting the need for a fundamental understanding of bacterial types. Bacteria can be generally classified into two main groups: gram-positive and gram-negative bacteria (Sharma et al., 2021b). Gram-positive bacteria have thick peptidoglycan layers in their cell walls, while gram-negative bacteria have thinner peptidoglycan layers and an extra outer membrane made up of lipopolysaccharides (Mahmoudi et al., 2011). This extra membrane in gram-negative bacteria, often referred to as the periplasm, may contribute to NPs resistance. However, this resistance is not insurmountable, and NPs remain valuable for their antibacterial effects and their potential to combat intracellular microorganisms due to their incredibly small size. Nanoparticles (NPs) engage with bacteria through diverse mechanisms, such as electrostatic attraction, van der Waals forces, receptor-ligand interactions, and hydrophobic interactions. These mechanisms enable NPs to make contact with bacteria, which is crucial for their antibacterial effects (Foley and Simeonov, 2012; Armentano et al., 2014; Mahmoudi et al., 2011; Gao et al., 2014). To disrupt bacterial function, NPs interact with the cellular machinery of bacteria, which can lead to electrolyte imbalances, oxidative stress, structural changes, alterations in cell membrane permeability, enzyme inhibition, protein deactivation, and changes in gene expression levels (Kaur et al., 2019; Shrivastava et al., 2007; Xu et al., 2016a, 2016b). The most commonly proposed mechanisms in research include oxidative and non-oxidative stress, cell wall penetration, the generation of reactive oxygen species (ROS), and the release of metal ions, as depicted in Fig. 8 (Zakharova et al., 2015; Gurunathan et al., 2012; Sangaiya and Jayaprakash, 2018; Leung et al., 2014). Oxidative stress refers to an imbalance between the production of ROS and the ability of cells to detoxify them, leading to potential damage to cellular components. When a bacterium is exposed to oxidative stress, the high levels of ROS generated can cause damage to

Table 7
Photocatalytic activity of TiO2 with different dyes.

S. No.	Phase	Size (nm)	Dye	Degradation (%)	References
1.	Anatase	11–14	Rhodamine B	97–98	(Kong et al., 2015)
2.	Anatase	10–20	Methylene blue	90–95	(Myilsamy et al., 2015)
3.	Anatase	10–15	Methyl orange	95–100	(Khalid et al., 2015)
4.	Anatase	40–100	Congo red	90–95	(Diantoro et al., 2018)
5.	Anatase	10–15	Methyl orange	97–100	(Jabbari et al., 2016)
6.	Anatase	10–20	Rhodamine B	95–98	(Zhang et al., 2016)
7.	Anatase	4–6	Methylene blue and Methyl orange	90–100	(Camposeco et al., 2016)
8.	Anatase	20–30	Phenol	85–90	(Pellegrino et al., 2017)
9.	Anatase and rutile	23–26	Rhodamine B	95–100	(Ahmed et al., 2017)
10.	Anatase	7–10	Methyl orange	95–100	(Zheng et al., 2017)
11.	Anatase	22–46	Phenol	90–100	(Gołąbiewska et al., 2017)
12.	Anatase	18–32	Phenol	90–100	(Mino et al., 2018)
13.	Anatase	10	Methyl orange	90–100	(Cho et al., 2021)
14.	Anatase	30–80	Phenol	95–98	(Zhao et al., 2018)
15.	Anatase	2–20	Rhodamine B, Methyl orange and Phenol	90–98	(Zhang et al., 2018a, 2018b)
16.	Anatase and rutile	5–40	Remazol black B	90–95	(Sheshmani and Nayebi, 2019)
17.	Anatase	10–25	Methylene blue	97–99	(Chinh et al., 2019)
18.	Anatase	7–10	Methylene blue	85–100	(Alosfur et al., 2019)
19.	Anatase and rutile	12–15	Rhodamine B	90–100	(Zhang et al., 2019)
20.	Anatase	20	Methylene blue	92–98	(Datcu et al., 2019)
21.	Anatase	20–100	Methylene blue and Methyl orange	90–100	(Temerov et al., 2020)
22.	Anatase	2–5	Rhodamine B	90–97	(Le et al., 2021)
23.	Anatase	15–18	Methylene blue	90–100	(Abbad et al., 2020)
24.	Rutile	10–15	Methylene blue	95–98	(Prasad et al., 2020)
25.	Anatase	15–25	Methyl orange	90–100	(Chen et al., 2020)

its proteins, lipids, and nucleic acids. This oxidative damage disrupts vital cellular functions and may ultimately lead to cell death (Jimoh et al., 2022). Non-oxidative stress encompasses various forms of stress that do not involve reactive oxygen species but still induce harmful effects on bacterial cells. Non-oxidative stress factors may include changes in pH, temperature, or osmotic pressure. These stressors can disrupt bacterial cell homeostasis and compromise essential cellular functions, contributing to antibacterial effects (Saini and Kumar, 2023). Antibacterial agents may penetrate the bacterial cell wall through various mechanisms, such as diffusion, active transport, or membrane disruption. Once inside the bacterial cell, the antibacterial agent can interfere with critical cellular processes, disrupt structural integrity, or target essential components, leading to impaired bacterial growth or cell death (Hameed and Abdulrahman, 2023). ROS include molecules like superoxide radicals, hydrogen peroxide, and hydroxyl radicals, which are highly reactive and can damage cellular structures. ROS can target bacterial proteins, DNA, and lipids, disrupting vital cellular functions. This oxidative damage can overwhelm the bacterial defense mechanisms, leading to cell death or impaired growth (Albukhaty et al., 2022). Some antibacterial agents can release metal ions (e.g., copper, silver) either through direct contact or as part of the agent's mechanism of action. Metal ions can disrupt bacterial cell membranes, interfere with enzymatic processes, and induce oxidative stress. These actions collectively contribute to antibacterial effects by compromising the integrity and function of bacterial cells (El Gohary et al., 2023). The antibacterial effects involve a combination of oxidative and non-oxidative stressors, penetration of the bacterial cell wall, generation of reactive oxygen species, and release of metal ions. These mechanisms collectively target various aspects of bacterial physiology, leading to cell damage or death and contributing to the efficacy of antibacterial agents (Aravind et al., 2023). TiO_2 NPs have garnered significant attention due to their promising antibacterial properties. Research by Tariq et al. (2022) demonstrated that TiO_2 NPs exhibit potent antibacterial activity through multiple mechanisms. One key mechanism is photocatalysis, wherein TiO_2 NPs, when exposed to UV light, generate ROS that induce damage to bacterial cell membranes and DNA. This photocatalytic effect has been proven effective against a wide spectrum of bacterial pathogens, including *Vibrio cholerae*. In the quest to enhance the antibacterial activity of TiO_2 NPs, Shimi et al. (2022) focused on optimizing the size and morphology of TiO_2 NPs to maximize their surface area and, consequently, their antibacterial efficacy. The results revealed that smaller-sized NPs with a specific morphology exhibited superior antibacterial properties, paving the way for more targeted applications. Complementary studies, such as the one conducted by Ansari et al. (2022), investigated the synergistic effects of combining TiO_2 NPs with other antibacterial agents. The combination of TiO_2 NPs with antibiotics or other NPs demonstrated enhanced antibacterial activity, overcoming some limitations associated with individual treatments. This research not only underscored the versatility of TiO_2 NPs but also provided practical insights into potential combinatorial strategies for more effective antibacterial applications. Sebak et al. (2022) investigated the antibacterial efficacy of TiO_2 NPs against drug-resistant strains of *Staphylococcus aureus* and *Escherichia coli*, highlighting the potential of TiO_2 NPs as a promising solution in the face of antibiotic resistance challenges. In conclusion, the antibacterial activity of TiO_2 NPs has been extensively studied with research focusing on elucidating mechanisms, optimizing NPs characteristics, exploring synergistic approaches, and applying these NPs against diverse bacterial pathogens. The collective findings underscore the potential of TiO_2 NPs as a versatile and effective tool in the fight against bacterial infections, opening new avenues for further research and practical applications. Table 8 provides a compilation of various researchers who have conducted work on the synthesis of TiO_2 NPs and their corresponding antibacterial activities, highlighting the growing interest in harnessing the potential of TiO_2 NPs for antibacterial applications. TiO_2 NPs have demonstrated promising antibacterial properties, yet several challenges and exciting prospects define their future in this domain. One challenge is the optimization of TiO_2 NPs for enhanced antibacterial efficacy. Researchers are actively exploring modifications to the NPs surface, size, and morphology to improve their interaction with bacterial cells and maximize antibacterial activity. Another challenge lies in addressing the selectivity of TiO_2 NPs, ensuring they target pathogenic bacteria while sparing beneficial microorganisms. Achieving this selectivity is crucial for the development of safe and targeted antibacterial applications. The future scope of TiO_2 NPs in antibacterial activity involves advancing their application beyond traditional surfaces to include medical implants, wound dressings, and other healthcare settings. Integration into polymers or coatings for sustained release and controlled delivery of TiO_2 NPs is a potential avenue. Additionally, exploring synergistic effects with other antimicrobial agents and understanding the mechanisms underlying

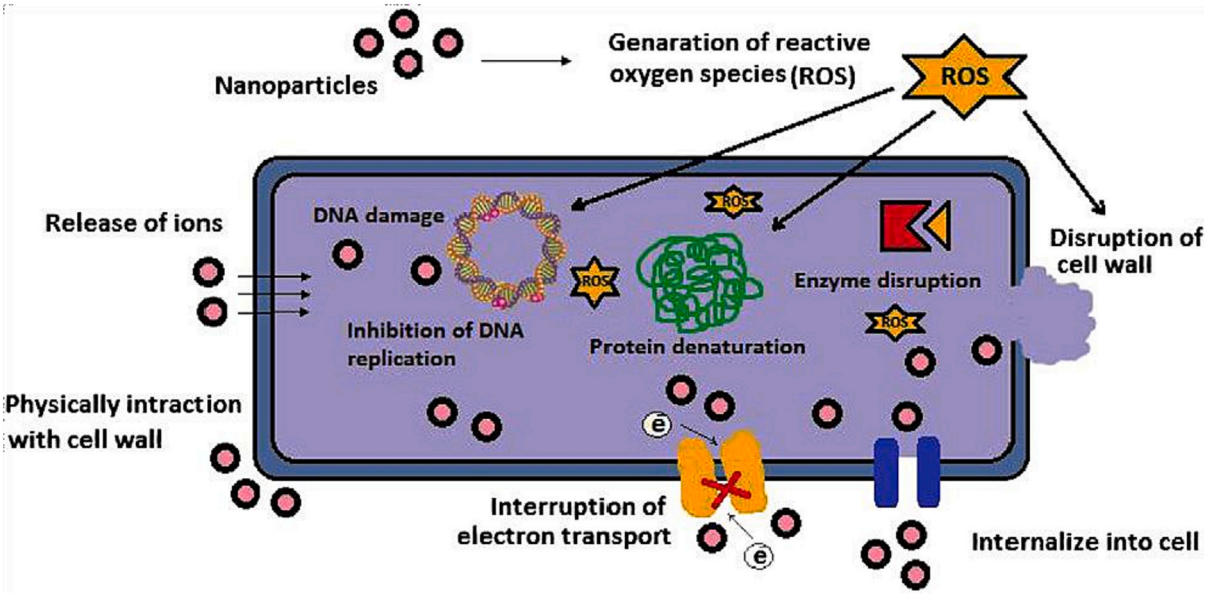

Fig. 8. Mechanism of antibacterial activity, Reprinted with permission from Elsevier (License No.: 5240161200712) (Dizaj et al., 2014).

antibacterial activity will further enhance their effectiveness. As the field progresses, efforts should focus on standardizing testing protocols and addressing potential environmental and health concerns associated with TiO_2 NPs. Balancing innovation with safety considerations will be pivotal for realizing the full potential of TiO_2 NPs in diverse antibacterial applications.

4.3. Antioxidant activity

The importance of antioxidants in maintaining cellular health has been well-established, with numerous studies and publications supporting this notion (Bandara et al., 2007; Cong et al., 2014). While the body's natural endogenous antioxidant defense mechanisms are generally effective at handling free radicals, in cases where disease development reaches a critical threshold, the role of exogenous antioxidants becomes crucial (Pouran et al., 2014). Recently, the rapidly advancing field of nanotechnology has shown great promise, potentially offering even more effective solutions than dietary exogenous antioxidant sources (Patrick-Iwuanyanwu et al., 2014). One practical way to assess the antioxidant activity of nanoparticles is through the color change of a 2,2-diphenyl-1-picrylhydrazyl (DPPH) solution. The presence of functionalized metal oxide nanoparticles can cause the DPPH solution to change from a deep violet color to pale yellow, enabling a visual means of monitoring antioxidant activity (Sharpe et al., 2011). Future particle size measurement techniques may leverage the size-dependent activity of NPs as a cost-effective and energy-efficient alternative, provided that the antioxidant activity assay is refined (Urso and Clarkson, 2003). Iron oxide NPs, with their inherent antioxidant qualities, hold the potential to extend the lifespan of critical materials (Yehye et al., 2015). Given the abundant availability of iron as a natural resource, this approach is financially viable (Armstrong et al., 2013). There are various methods for assessing antioxidant properties, including biological assays such as Cellular Antioxidant Activity (CAA) (Huang et al., 2019) and chemical-based methods like Ferric Reducing Ability of Plasma (FRAP) (Naik et al., 2010) and Cupric Reducing Antioxidant Capacity (CUPRAC) assays (Lee et al., 2017), among others. These assays provide valuable insights into the antioxidant capabilities of various substances, including NPs.

The antioxidant activity of NPs is closely related to their capacity to scavenge free radicals, particularly in assays involving DPPH. Extensive research has been conducted to explore the potential of NPs as effective materials for treating diseases caused by the presence of free radicals (Benzie and Strain, 1996). The increased antioxidant activity observed in TiO_2 NPs can be attributed to their higher surface area, allowing for a more significant reaction for a given weight of the material (Çelik et al., 2010). In the study of antioxidant properties, the mechanisms of action can be categorized into two primary types based on the chemical reactions involved in various assays (Durmaz, 2012), as depicted in Fig. 9. These mechanisms are electron transfer and hydrogen atom transfer (Paul et al., 2009). The observed antioxidant property of DPPH involves the neutralization of free radicals through the transfer of an electron (Shah et al., 2017). Table 9 provides a compilation of various researchers who have conducted work on the synthesis of TiO_2 NPs and their corresponding antioxidant activities. This reflects the growing interest in understanding the potential of TiO_2 NPs as effective antioxidants and their application in various fields. The application of TiO_2 NPs in antioxidant activity presents both challenges and promising avenues for future exploration. One challenge is optimizing the antioxidant properties of TiO_2 NPs, particularly in terms of scavenging ROS. Enhancing the efficiency of ROS capture and mitigating potential cytotoxicity are areas of ongoing research to ensure the safety and effectiveness of TiO_2 NPs as antioxidants. Another challenge involves the need for a comprehensive understanding of the biological interactions of TiO_2 NPs. Addressing issues related to biocompatibility, biodistribution, and long-term effects is crucial for their successful integration into biomedical applications as antioxidants. The future scope of TiO_2 NPs in antioxidant activity includes their potential application in pharmaceuticals, nutraceuticals, and functional foods. Researchers are exploring innovative strategies to improve bioavailability and sustained release for optimal antioxidant effects. Additionally, the development of hybrid materials and surface modifications is anticipated to enhance the overall antioxidant performance of TiO_2 NPs. As the field progresses, it is essential to establish standardized testing methodologies and safety guidelines. Striking a balance between harnessing the antioxidant potential of TiO_2 NPs and addressing associated challenges will be pivotal for realizing their broad applications in promoting health and well-being.

4.4. TiO_2 nanohybrids

TiO_2 NPs have gained significant attention and found numerous novel applications due to their exceptional electrical, optical, and

Table 8
TiO_2 NPs against antibacterial activity.

S. No.	Phase	Size	Bacteria	References
1.	Anatase	62–74	*Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumoniae* and *Bacillus subtilis*	(Rajakumar et al., 2012)
2.	Anatase	40–60	*Escherichia coli*	(Ordenes-Aenishanslins et al., 2014)
3.	Anatase	32–58	*Staphylococcus aureus* and *Escherichia coli*	(Santhoshkumar et al., 2014)
4.	Anatase	28–54	*Staphylococcus aureus,* and *Streptococcus pyogenes*	(Podporska-Carroll et al., 2015)
5.	Anatase	35–70	*Staphylococcus aureus*	(Lee et al., 2015)
6.	Anatase	2–5	*Escherichia coli* and *Staphylococcus aureus*	(Luo and Huang, 2015)
7.	Anatase	2–10	*Escherichia coli*	(Zimbone et al., 2015)
8.	Anatase	2–50	*Staphylococcus aureus*	(Wang et al., 2016)
9.	Anatase	15–26	*Escherichia coli* and *Staphylococcus aureus*	(Ambika and Sundrarajan, 2016)
10.	Anatase	15–20	*Vibrio cholerae, Pseudomonas aeruginosa, Shigella flexneri*	(Vijayalakshmi and Sivaraj, 2016)
11.	Anatase	12–13	*Escherichia coli, Salmonella typhimurium Staphylococcus aureus* and *Bacillus cereus*	(Jalali et al., 2016)
12.	Anatase and rutile	33	*Escherichia coli* and *Staphylococcus aureus*	(Mahdy et al., 2017)
13.	Anatase	17	*Escherichia coli*	(Alhadrami et al., 2017)
14.	Anatase	15–19	*Staphylococcus aureus, Bacillus subtilis, Escherichia coli, Pseudomonas aeruginosa, Candida albicans* and *Aspergillus niger*	(Sundrarajan et al., 2017)
15.	Anatase	35	*Klebsiella aerogenes, Escherichia coli, Pseudomonas desmolyticum* and *Staphylococcus aureus*	(Razzaq et al., 2021)
16.	Anatase	30–50	*Klebsiella aerogenes, Escherichia coli, Pseudomonas desmolyticum and Staphylococcus aureus*	(Li et al., 2018)
17.	Anatase	3–5	*Escherichia coli*	(Tian et al., 2018)
18.	Anatase and rutile	25–40	*Escherichia coli*	(Hosseini et al., 2019)
19.	Anatase	30–60	*Staphylococcus aureus* and *Escherichia coli*	(Nguyen et al., 2019)
20.	Anatase	25–30	*Escherichia coli* and *Staphylococcus aureus*	(Anandgaonker et al., 2019)
21.	Rutile	8–10	*Bacillus subtilis and Pseudomonas aeruginosa*	(Akhtar et al., 2019)
22.	Anatase	70–80	*Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus* and *Bacillus subtilis*	(Menazea and Awwad, 2020)
23.	Anatase	20–80	*Bacillus cereus, Clostridium tetani, Escherichia coli* and *Vibrio cholerae*	(Aswini et al., 2021)
24.	Anatase	11–16	*Escherichia coli, Acinetobacter baumannii, Staphylococcus aureus* and *Enterobacter cloacae*	(Boudghene-Guerriche et al., 2020)
25.	Anatase	14–15	*Escherichia coli*	(Rokicka-Konieczna et al., 2020)

catalytic properties (Wicklein et al., 2015). However, one challenge with TiO_2 NPs is their propensity to be unstable and rapidly aggregate during synthesis, which can affect their performance (Sharma et al., 2019). Many researchers believe that this issue can be addressed by immobilizing the catalyst on a suitable substrate (Xu et al., 2016a, 2016b). TiO2

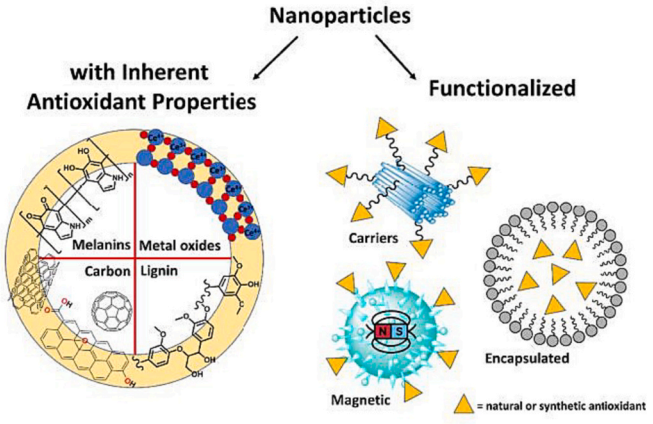

Fig. 9. Mechanism of antioxidant activity, (Copyright © 2021 by the authors. Licensee MDPI, Basel, Switzerland) (Baschieri and Amorati, 2021).

Table 9
TiO_2 NPs against antioxidant activity.

S. No.	Phase	Size (nm)	Assay	References
1.	Anatase	25–30	DPPH	(Shetty et al., 2015)
2.	Anatase	10–15	Enzyme	(Ghorbanpour et al., 2015
3.	Anatase	30–200	DPPH	(Kumar et al., 2016)
4.	Anatase	21	3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT), Lactate dehydrogenase and Propidium iodide (PI)	(Runa et al., 2016)
5.	Anatase	20	Enzyme	(Wu et al., 2017)
6.	Anatase	20	Ascorbic acid	(Bajic et al., 2017)
7.	Anatase	10–24	2,2-Azino-bis (3-ethyl Benzthiazoline-6- sulfonic acid) (ABTS)	(Hassan et al., 2018)
8.	Anatase	10–35	DPPH	(Alavi and Karimi, 2018)
9.	Anatase	20	DPPH	(Rikabad et al., 2019)
10.	Anatase	45–200	DPPH	(Ajmal et al., 2019)
11.	Anatase	2–7	DPPH	(Feng et al., 2019)
12.	Anatase	25–50	DPPH	(Bhardwaj and Singh, 2021)

NPs, thanks to the presence of surface hydroxyl groups, can also serve as green templates or supporting materials for the creation of nanohybrid materials. These materials can be easily modified through chemical synthesis and physical adsorption of other species, and they exhibit water stability (Cirtiu et al., 2011). Over the past decade, TiO_2 NPs and other nanohybrid-based materials have predominantly been employed in materials science applications. However, the utilization of these materials in the fields of energy, environmental science, agriculture, and biological research remains relatively limited, with a range of 1.17–5.63 % of publications (Gong et al., 2019). Consequently, the number of research papers and outcomes related to TiO_2-based nanohybrids remains relatively scarce, signaling a need for further exploration of their potential applications and benefits in various fields as shown in Fig. 10.

Metal-metal nanohybrids, such as TiO_2 nanohybrids, involve the combination of TiO_2 with different metallic components to create multimetallic ensembles. These metallic components can serve various functions, including plasmonic, magnetic, semiconducting oxides, quantum dots, and more (Sun et al., 2011). The synthesis of conjugated

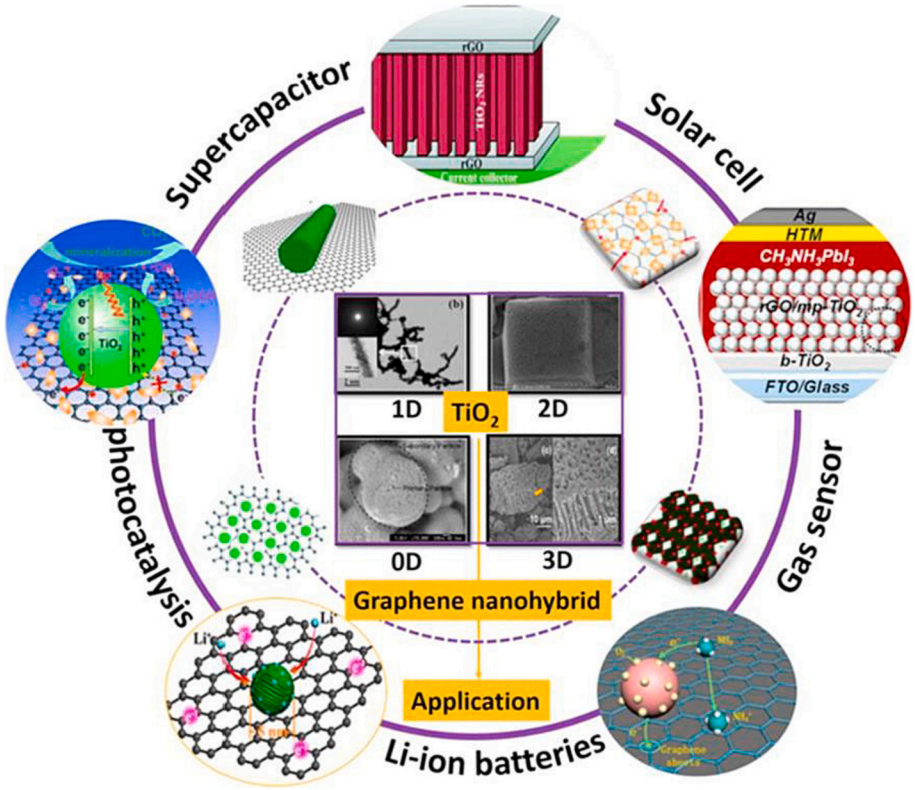

Fig. 10. TiO_2 nanohybrids in various fields, Reprinted with permission from Elsevier (License No.: 5240200018959) (Yu et al., 2017).

TiO_2 nanohybrids involves various techniques tailored to the desired properties, structures, and applications (Pena et al., 2009). Among the most common synthesis methods are wet chemical reactions that reduce or thermally decompose metal salts. Examples of these methods include polyol processes, photochemical deposition, electroless plating, solvothermal hydrothermal synthesis, sol-gel methods, ion implantation, and epitaxial growth (Kim et al., 2013a, 2013b; Anandan et al., 2008). Core-shell nanostructures can be created through co-reduction or sequential reduction processes using vapor-gas phase techniques like aerosol and plasma-assisted deposition. In some cases, a subsequent metal nanohybrid with different chemical properties may be required to build upon a previously formed metal nanohybrid (Liu et al., 2013a, 2013b). To achieve patterned growth, optical lithography is often combined with other methods. Using template-based growth techniques, hollow spherical, porous, or tubular structures can be fabricated. These techniques utilize matrices like inorganic silica, the oil-water interface, polymers, or *block-co*-polymer matrices. Matrix-bound techniques create nanohybrids through co-precipitation, ion implantation, emulsification, and reverse micellization (Fan et al., 2011). In some cases, inorganic or organic linkers or spacers may be employed between the metallic core and shell layers to fine-tune the properties and interactions of the nanohybrid materials. Additionally, natural extracts have been used as reducing or solvent agents in biogenic or green synthesis processes for nanohybrids, contributing to sustainable and environmentally friendly approaches (Chen et al., 2010). These diverse synthesis methods enable the creation of multifunctional nanohybrids with tailored properties for a wide range of applications in fields such as materials science, catalysis, and nanotechnology.

Nanohybrids offer a range of advantages in various applications due to the synergistic properties they possess, making them versatile in fields such as photovoltaics, biomedical engineering, catalysis, chemical sensing and degradation, and antibacterial applications (Shankar et al., 2004). In photovoltaics, nanohybrids have proven to be valuable. For instance, in dye-sensitized solar cells, co-axial Ag-TiO_2 core-shell nanowire arrays with a high specific surface area and efficient electron transport can enhance the efficiency of electron collection (Bigall et al., 2012). These advancements can contribute to more effective and sustainable solar energy conversion. In biomedical applications, nanohybrids are employed for various purposes, including separating cancer cells from cell mixtures and inducing photothermal death of these cells using near-infrared (IR) radiation. Additionally, they are used to enhance contrast in magnetic resonance imaging (MRI) for disease and pathogen detection. The plasmonic properties of TiO_2 nanohybrids offer efficient methods for detecting disease-specific proteins through techniques like surface plasmon resonance (SPR) and surface-enhanced Raman scattering (SERS) (Asgari et al., 2013; Liu et al., 2013a, 2013b; Li et al., 2011). Moreover, the photoluminescent properties of semiconducting quantum dots can be enhanced when they are combined with magnetic or plasmonic particles, making them valuable for fluorescence microscopy and bioimaging (Achilleos and Vamvakaki, 2010). In the field of catalysis, nanohybrids, particularly TiO_2 nanohybrids, have shown increased photocatalytic activity when exposed to UV or visible light. Their efficient charge separation and charge transfer processes make them suitable for degrading organic contaminants and inactivating bacteria (Qiu et al., 2012; Kirschling et al., 2011). Nanohybrid ensembles derive their multifunctionality from the nonlinear synthesis of useful properties from each contributing nanostructure. These assemblages enhance functionality while also displaying novel and unanticipated physicochemical properties, which may have unforeseen environmental implications. As researchers focus on the advantages of nanohybrids, investigations into their potential harmful and environmental consequences have gained traction in recent years. It is essential to adopt a comprehensive strategy to assess and manage the environmental impact of these nanohybrids and ensure their safe and sustainable use in various applications. The integration of TiO_2 NPs into nanohybrid applications presents challenges and holds immense potential for diverse future applications. One significant challenge is achieving synergistic compatibility with other nanomaterials to create

efficient and stable nanohybrids. The selection of appropriate materials and optimizing their interactions is crucial to harnessing the desired properties for specific applications. Another challenge involves the need for scalable and cost-effective synthesis methods for TiO_2 nanohybrids. Overcoming production challenges will be essential for realizing the widespread implementation of these advanced materials in various industries. The future scope of TiO_2 NPs in nanohybrid applications is expansive. These nanohybrids can find applications in areas such as catalysis, sensing, energy storage, and drug delivery. Tailoring the properties of TiO_2 nanohybrids through innovative combinations with other nanomaterials can lead to multifunctional materials with enhanced performance and unique functionalities. In the realm of nanomedicine, TiO_2 nanohybrids may offer targeted drug delivery systems with controlled release profiles, combining therapeutic and diagnostic capabilities. Moreover, the incorporation of TiO_2 nanohybrids in energy storage devices and environmental remediation technologies holds promise for sustainable and efficient solutions. As research progresses, addressing environmental and safety concerns associated with TiO_2 nanohybrids and establishing regulatory frameworks will be crucial for realizing their full potential in the emerging landscape of nanotechnology applications.

5. Challenges and opportunities

The exploration of photocatalytic, antibacterial, antioxidant, and nanohybrid applications of anatase and rutile TiO_2 NPs presents a multifaceted landscape of challenges and opportunities. Enhancing the efficiency and selectivity of photocatalysis remains a primary challenge. Addressing rapid charge recombination and developing strategies to harness visible light effectively are pivotal hurdles to overcome. Understanding the precise antibacterial mechanisms of TiO_2 NPs and achieving consistency in antibacterial performance across various strains and resistance profiles are ongoing challenges. The variability in results regarding the antioxidant properties of TiO_2 NPs underscores the need for standardized testing methodologies and a deeper understanding of their role in combating oxidative stress. The potential toxicity of TiO_2 NPs in various applications necessitates rigorous evaluation and risk assessment, especially in the context of nanohybrid systems intended for biomedical use. The incorporation of dopants and co-dopants into TiO_2 NPs offers a promising avenue to extend their photoresponse into the visible range, expanding their applications in photocatalysis. Fine-tuning the shape and crystal structure of TiO_2 NPs provides opportunities to optimize their antibacterial properties, enabling the development of more effective antibacterial agents. The research into TiO_2 nanohybrids for biomedical applications opens up opportunities for novel drug delivery systems, imaging agents, and therapeutic interventions with the potential to revolutionize healthcare. The photocatalytic properties of TiO_2 NPs offer substantial potential for addressing environmental challenges, including air and water purification, as well as the degradation of pollutants. The versatility of TiO_2 NPs in exhibiting photocatalytic, antibacterial, and antioxidant properties within nanohybrid systems underscores their potential to revolutionize multiple technology sectors, from healthcare to environmental conservation. In conclusion, while there are significant challenges to overcome in harnessing the full potential of anatase and rutile TiO_2 NPs in the mentioned applications, the opportunities are equally substantial. Continued research and innovation in materials science and nanotechnology hold the promise of unlocking the transformative capabilities of these NPs, contributing to advancements in fields ranging from public health to sustainability.

6. Conclusions

Over the past two decades, extensive research efforts have been dedicated to the synthesis and modification of TiO_2 NPs, unlocking a plethora of new properties and applications. The production of TiO_2 NPs in varied shapes, including nanorods, nanotubes, and nanowires, underscores the critical influence of size and structure on their optical, electrical, thermal, and structural characteristics. This comprehensive review explores the evolving properties, adaptations, and applications of TiO_2 NPs while contemplating their future prospects. One major challenge in the field of TiO_2 NPs pertains to photocatalysis, where issues like rapid charge recombination and inefficient utilization of visible light have hindered efficacy. Researchers have sought solutions by exploring electron donors to interact with valence band holes, inhibiting charge recombination. Doping and co-doping with impurity energy levels have extended TiO_2's photoresponse into the visible range, enhancing photocatalytic activity and charge separation. TiO_2 NPs exhibit significant promise in antibacterial applications, with their shape and crystal structure crucial in determining efficacy against gram-positive and gram-negative bacteria, including antibiotic-resistant strains. Controlling the shape and crystal structure is pivotal for maximizing their antibacterial potential. The antioxidant properties of TiO_2 NPs have been a subject of interest, with assessments involving tests like DPPH and free radical scavenging assays. However, mixed results have been reported, comparing TiO_2 NPs with plant extracts in terms of antioxidant capacity. This review also delves into TiO_2 nanohybrids, gaining attention for biomedical applications. While some inorganic nanohybrids are commercially available, numerous others have been explored but not widely disseminated. The research landscape yields varied results, emphasizing the versatility and importance of TiO_2 NPs in technological domains. Continued research holds the potential to usher in a new generation of TiO2 NPs tailored for diverse applications, shaping the future of nanotechnology and its practical implementations.

CRediT authorship contribution statement

Nikesh Thakur: Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Vijay Kumar Thakur:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Susheel Kalia:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Vedpriya Arya:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ashwani Kumar:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Sunil Kumar:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **George Z. Kyzas:** Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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