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Biogenic Synthesis of TiO_2 Nanoparticles using Plant Extracts and Their Potential Applications: A Review

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Abstract: Nanomaterials have gained a lot of attention over past few decades due to their advance physical and chemical properties as compared to bulk materials. The synthesis of nanoparticles (NPs) often involves a number of physical and chemical procedures. Biosynthesis plays a crucial role in synthesis of nanoparticles due to cost-effective, non-toxic and sustainable advantages. This review focuses on the biogenic synthesis of TiO_2 using plant extracts derived from flowers, stem, leaves, etc. The plant extracts contain various therapeutic compounds like alkaloids, terpenoids, saponins, proteins, amino acids, vitamins which act as both capping and stabilizing agent. This review also reports the antibacterial can photocatalytic activity of TiO_2 which make them employable in various fields like food, pharma, industries and electronics.

Keywords: Nanoparticles, Biosynthesis, TiO_2, Antibacterial, Photocatalytic

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Introduction

A famous quote "There is Plenty of Room at the Bottom", in a speech given by Nobel Laureate Richard Feynman at the American Physical Society conference in 1959 which is believed to given the inspiration for the research and development in the field of nanoscience and nanotechnology (Feynman, 1959). Nanotechnology is one of the most captivating fields for developing and employing materials comprising of interatomic structural properties. Nanoparticles can be defined as particles with sizes that range between 1-100 nm and having at least one dimension on a scale of one-billionth of a meter (Findik, 2021). In the past three decades, nanoscience has made significant strides towards creating cutting-edge functional materials which are beneficial in various areas like catalysis, industries, agriculture, molecular diagnosis, electronics, food industry and many more. When compared to bulk materials like powders, plates, and sheets, nanoparticles have an extremely high surface area to volume ratio and due to their tiny size, which allows them to confine their electrons and initiate quantum effects that offers intriguing optical, physical, and chemical properties in the nanoparticles (Asha nd Narain, 2020; Khan and Hossain, 2022).

Nanoparticles can be synthesized by two approaches namely bottoms-up and top-down. In top-down approach, external tools are employed in a controlled manner to shape materials down into nano size by cutting or grinding. Some of the most frequently employed top-down methods are lithography, laser ablation, mechanical milling, thermal decomposition, sputtering, grinding etc. Whereas in bottoms-up approach particles are self-assembled in atom-by-atom, molecule-by-molecule, or cluster-by cluster fashion which has the ability to control shape, size and morphology of desired nanoparticles by modulating experimental parameters like pH, temperature, reaction time etc. (Abid *et al*., 20./22). The process of creating nanoparticles *via* bottom-up technique often results in the deposition of hazardous metal ions and/or organic compounds on the surface of the nanoparticles which hampers its biomedical applications (Mohammadi *et al*., 2016). To overcome this problem, the merging of Green Chemistry and nanotechnology has led to the fabrication of eco-friendly nanoparticles. Green syntheses of nanomaterials include synthesis using environmentally benign solvent systems aided by plant ingredients, bacteria, fungus, algae etc. which is cost-effective, biocompatible and safe (Makarov *et al*., 2014).

Among the group of various metals and metal oxides, TiO_2 is one of the versatile compounds that exists in three crystalline forms anatase, rutile, and brookite. Out of these three forms, anatase possesses wide range of applications due to its low toxicity, high photoactivity, biocompatibility, strong corrosion resistance and chemical stability. The electron-hole combination and small surface area are only drawbacks of TiO_2 NPs, however, having an energy gap of 3.2eV, TiO_2 uses UV lights instead of visible light. Despite these drawbacks, TiO_2 NPs have found increasing applications in various industrial products which are used in ordinary house hold such as cosmetics, lotions, skin ointments, creams, food colourants, papers, paints and inks (Fujishima and Zhang, 2006; Haider *et al*., 2019; Kang *et al*., 2019).

The current review discusses the green synthesis of TiO_2 NPs reposted in literature which has employed different parts of plants like roots, flower, leaf, etc. for various applications. The attention is developing due to its self-cleaning and photocatalytic activity, excellent band gap, and antibacterial agent as well as physic-chemical stability.

Biosynthesis of Titanium Oxide NPs

According to the principles of green chemistry, the green synthesis approaches use the biological constituents. Stable, tiny, and less agglomerated metal and metal oxide nanoparticles may be produced using this cost effective and environmentally benign synthetic method (Nair *et al*., 2022). The plants contain various phyto-nutrients like flavonoids, phenols, amino acids, carbohydrates, saponins, terpenes, etc., with the activation of the precursors, these phytochemicals initiate the process of NP synthesis. Moreover, various components of the plant extracts act as a reducing agent and suppresses nanoparticles aggregation (He *et al*., 2017; Chowdhury *et al*., 2021). The different plant components which have been utilized for TiO_2 synthesis is discussed below:

(a) *Synthesis of TiO_2 via leaf extract*

The leaf extracts of various plants have been widely used as a reducing and capping agent for the green synthesis of TiO_2 nanoparticles as shown in Table 1. Leaf extracts of *Tulbaghia violacea* was used for the green synthesis of TiO_2 NPs. The synthesized TiO_2 NPs were rectangular in shape with average size distribution of 10-50 nm

Table 1: Synthesis TiO_2 NPs using leaf extracts

S. No.	Plant (Family)	Common Name	Size (nm)	Shape	Activity	Ref.
1	*Tulbaghia violacea* (Amaryllidaceae)	Society Garlic	10-50 nm	Rectangular	Antioxidant and anticancer activity	Mbenga *et al.* (2023)
2	*Acorus calamus* (Acoraceae)	Sweet Flag	15-40 nm	Semi-spherical	Antibacterial and Photocatalytic activity	Ansari *et al*. (2022)
3	*Pouteria campechiana* (Sapotaceae)	Eggfruit tree	--	Spherical	Larvicidal and pupicidal activities against *Aedes aegypti*.	Narayanan *et al.* (2021)
4	*Mentha arvensis* (Lamiaceae)	Mint	20-70 nm	Spherical	Antibacterial activity against *E. coli*, *P. vulgaris*, *S. aureus* and antifungal activity against *A. niger*, *A. fumigates*, *A. cuboid*	Ahmad *et al.* (2020)
5	*Carica papaya* (Caricaceae)	Papaya	20 nm	Spherical	Photocatalytic activity against degradation of reactive orange 4 dye	Kaur *et al.* (2019)

as revealed by SEM and XRD studies. This study also highlights the cytotoxicity of TiO_2 NPs against cancer cells HeLa and HEK293 compared to 5-Fluorouracil (Mbenga *et al*., 2023). Ansari *et al.* (2022) reported the formation of TiO_2 NPs using leaf extract of *Acorus calamus*. The presence of Ti-O and O-H vibration bands were confirmed by FTIR and XRD revealed the average size 15-40 nm. The synthesized NPs displayed excellent antimicrobial properties. In addition, the NPs showed photocatalytic activity against rhodamine dye by degrading 95.69% in 120 min of irradiation (Ansari *et al*., 2022). Similarly, the leaves of *Pouteria campechiana* of family Sapotaceae have been used for TiO_2 synthesis. The synthesized NPs were characterized by various complimentary techniques such as UV-Visible, SEM, XRD and FTIR. UV-Visible spectrum recorded the sharp peak at 320 nm which revealed the formation of TiO_2 NPs, SEM confirmed the spherical shape and FTIR showed prominent peak at 1052.41 cm^{-1} which corresponds to the bonding pattern of alcohol (Narayanan *et al*., 2021). In another study, titanium oxide NPs were synthesized using *Mentha arvensis* leaf extract with size of 20-70 nm range which possessed significant antibacterial and antifungal activity. XRD confirms the crystalline structure and the incidence of peaks at 25.27° which corresponds to 110 anatase form and SEM reveals the spherical shape (Ahmad *et al*., 2020). Some, TiO_2 NPs were also synthesized by using leaf extract of *Carica papaya*. FE-SEM confirmed the cages-like morphology, TEM revealed the particle size of 20 nm, FTIR spectrum showed the absorption band of Ti-O stretching in the region 750 cm^{-1} to 650 cm^{-1} and BET analysis recorded the mesoporous nature with surface area and mean pore size of 81.653 m^2g^{-1} and 8.0615 nm (Kaur *et al*., 2019). The researchers also evaluated the efficiency for photocatalytic degradation of reactive orange 4 dye in 180 min under UV exposure with dosage of 25 mg (Kaur *et al*., 2019).

(b) *Synthesis of TiO_2 via flower extract*

Biogenic synthesis of TiO_2 NPs using flower extracts has gained immense attention nowadays, as shown in Table 2. Rathi and Jeice (2023) used the greener strategy for the synthesis of TiO_2 NPs using flower extracts of *Ceaspina pulcherrima*. This study has furnished the anatase phase of NPs. The TEM images confirm the 15-28 nm size range with spherical morphology. The antimicrobial were also studied against *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Candida albicans* with zone of inhibition 9 mm, 6 mm, 7.2 mm and 5 mm, respectively. The synthesized TiO_2 NPs demonstrated photo-degradation activity towards methylene blue dye with 86% of degradation rate in 180 min under UV

Table 2: Synthesis TiO_2 NPs using flower extracts

S. No.	Plant (Family)	Common Name	Size (nm)	Shape	Activity carried out	Ref
1	*Ceaspina pulcherrima* (Fabaceae)	Peacock Flower	15-28 nm	Spherical	Antibacterial activity against S. aureus *E. coli P. aeruginosa C. albicans* and Photocatalytic activity against methylene blue dye	Rathi and Jeice (2023)
2	*Jasminum* (Oleaceae)	Jasmine	31-42 nm	Spherical	Hydroxyl group present to enhance photocatalytic activity	Aravind *et al.* (2021)
3	*Matricaria chamomilla* L (Asteraceae)	Chamomile	10-20 nm	Tetragonal	Enhancement of surface energy by minimising agglomeration	Pakseresht *et al.* (2021)
4	*Hibiscus rosasenansis* (Malvaceae)	Hibiscus	7 nm	Spherical and Monodispersed	Antibacterial activity against *V. cholerae, P. aeruginosa, S. aureus*	Kumar *et al.* (2014)
5	*Calotropis gigantea* (Apocynaceae)	Giant Milkweed	10.52 nm	Spherical	Acaricidal activity against *R. microplus* and *H. bispinosa*	Marimuthu *et al.* (2013)

exposure with dosage of 25 mg (Rathi and Jeice, 2023). The flower extract of jasmine was also employed for synthesizing spherical TiO_2 NPs and the authors reported the enhanced photocatalytic activity of synthesized NPs against methylene blue dye with 92% of degradation in 120 min under UV irradiation. The XRD data confirmed the crystalline nature of TiO_2 with size distribution of 31-42 nm and SEM revealed the spherical shape of synthesized NPs (Aravind *et al.*, 2021). Pakseresht *et al.* (2021) biosynthesized TiO_2 NPs by using *Matricaria chamomilla* flower extracts as reducing and stabilizing agents. The anatase tetragonal phase of NPs was confirmed by XRD and FE-SEM showed the 10-20 nm size of NPs having cauliflower morphology which maximise their surface area by reducing agglomeration (Pakseresht *et al.*, 2021). Similarly, Kumar *et al.* (2014) synthesized the titanium oxide NPs using titanium oxysulfate solution and hibiscus flower extract. The authors also reported the antibacterial activity against *Vibrio cholerae, Pseudomonas aeruginosa* and *Staphylococcus aureus* with zone of inhibition at 15 µg/ml, 13 µg/ml and 13,5 µg/ml, respectively. The monodispersed and spherical shape were confirmed by SEM, XRD peaks showed the crystalline nature and FTIR data revealed the presence of hydroxyl group (O-H)(Kumar *et al.*, 2014).

(c) *Synthesis of TiO_2 via peel extract*

The peel extracts of different plants can used as reducing as well as stabilizing agents for the synthesis of TiO_2 NPs, as shown in Table 3. Lemon peel extract were used for biogenic synthesis of TiO_2 NPs in which XRD result confirmed the anatase form and particle size 80-140 nm, UV-Visible revealed the band gap of 3.08eV and agglomerated structures were displayed by SEM analysis (Nabi *et al.*, 2022). Similarly, TiO_2 NPs were synthesized by using fruit peel of orange to analyse antibacterial activity against *E. coli, P. vulgaris* and *S. aureus* with zone of inhibition 10 mm, 9 mm and 12 mm, respectively. The authors also reported the anticancer activity of synthesized NPs against A549 cell lines at 400 µg/ml concentration (Amanulla and Sundaram, 2019). Likewise, by using the extract of Rambutan fruit peel, TiO_2 NPs were prepared via green route, the morphology of these nanorods was confirmed

Table 3: Synthesis TiO_2 NPs using peel extracts

S. No.	Plant (Family)	Common Name	Size (nm)	Shape	Activity carried out	References
1	*Citrus Limon* (Rutaceae)	Lemon	80-140 nm	Spherical	Optical and Photocatalytic activity	Nabi *et al.* (2022)
2	*Citrus sinensis* (Rutaceae)	Orange	20-50 nm	Triangular shape	Antibacterial activity against *E. coli, P. vulgaris, S. aureus* and anticancer activity of A549 cells	Amanulla and Sundaram (2019)
3	*Nephelium lappaceum* L (Sapindaceae)	Rambutan	70-90 nm	--	Cytotoxicity analysed using Breast cancer cells (MDA-MB-231) and death rate of cell = 73.65 µg/ml	Isacfranklin *et al.* (2021)

Table 4: Synthesis TiO_2 NPs using seed extracts

S. No.	Plant (Family)	Common Name	Size (nm)	Shape	Activity carried out	References
1	*Abelmoschus esculentus* (Malvaceae)	Okra or Ladyfinger	60-120 nm	Spherical	Photocatalytic activity	Aslam *et al.* (2022)
2	*Cuminum cyminum* (Apiaceae)	Cumin	15 nm	---	Effective free radical inhibition in DPPH assay	Mathew *et al.* (2021)
3	*Myristica fragrans* (Myristicaceae)	Nutmeg	2-100 nm	Spherical	Photocatalytic activity against the degradation of MB and Congo red dyes	Sagadevan *et al.* (2021)

by TEM with average diameter of 70-90 nm and XRD revealed the tetragonal structure. They also analyse the cytotoxicity using Breast cancer cells (MDA-MB-231) and death rate of cell spot at 73.65 µg/ml (Isacfranklin *et al*., 2021).

(d) *Synthesis of TiO_2 via seed extract*

Seeds are also well established for the synthesis of TiO_2 NPs, as shown in Table 4. Aslam *et al*. (2022) reported the biogenic synthesis of TiO_2 NPs using seed extract of Okra, which is used as both reducing as well as capping agent due to rich flavonoid content. In this study, synthesized NPs were found to be spherical in shape of size ranges between 60-120 nm and the authors reported the enhanced photocatalytic activity of synthesized NPs against methylene blue dye with 80% of degradation with 120 min of exposure under UV lamp of 250 watts (Aslam *et al.*, 2022). Similarly, outstanding antioxidant activity was also shown by using *Cuminum cyminum* (Jeera) seed extract at various concentration (25, 50 100, 150, 200, and 250 µg ml^{-1}) of TiO_2 NPs. In this study EDS analysis confirmed the presence of Titanium (Ti), XRD revealed the crystalline size of 15.17 nm and the seed germination of mung beans and plant growth parameters were also reported (Mathew *et al.*, 2021). Likewise, Sagadevan *et al.* (2021) studied the optical properties of green synthesized titanium oxide NPs using *Myristica fragrans* seed extract which indicates the blue shift and a band gap of 3.34eV. The photocatalytic activity synthesized NPs were confirmed the 99% in 40 min and 97% in 60 min degradation of Methylene

Table 5: Synthesis TiO_2 NPs using stem and root extracts

S. No.	Plant (Family)	Common Name	Part taken for extraction	Size (nm)	Shape	Activity carried out	References
1	*Tinospora cordifolia* (Menispermaceae)	Guduchi	Stem	15.02 nm	Triangular shape	Photocatalysis and Antibacterial activity	Saini and Kumar (2023)
2	*Rhizoma coptidis* (Ranunculaceae)	Huanglian	Root	24-32 nm	Hexagonal Shape	Photocatalytic activity of methylene blue and malachite green dyes	Sreekanth *et al.* (2017)
3	*Ageratina altissima* (Asteraceae)	White Snakeroot	Root	25 nm	Spherical	Surface area and pore size distribution evaluate from BET technique and BHJ model	Madadi and Bagheri Lotfabad (2016)
4	*Curcuma longa* (Zingiberaceae)	Turmeric	Root	50-110 nm	Spherical shape	---	Abdul Jalill *et al.* (2016)

blue and Congo red dye, respectively (Sagadevan *et al.*, 2021).

(e) *Synthesis of TiO_2 via stem and root extract*

Numerous stem and root extracts can be used for the synthesis of TiO_2 NPs, as shown in Table 5. TiO_2 NPs were also synthesized using *Tinospora cordifolia* stem extract. The synthesized NPs is triangular shaped with particle size 15.02 nm. In this study antibacterial activity were also carried out in which ZOI of synthesized TiO_2 NPs was measured as 13 ± 0.39 and 26.5 ± 0.79 mm, equivalent to150 and 500 µg/ml, respectively against *E. coli*. They have reported the 94% photocatalytic degradation of Acid Blue 113 in 80 min (Saini and Kumar, 2023). Hexagonal and rectangular morphology in nanostructured titanium oxide were derived by using root extract of *Rhizoma coptidis* and this study further demonstrated the photocatalytic activity towards the degradation of methylene blue (71% in 60 min) and malachite green (77% in 60 min) dyes under UV light and in the absence of light (Sreekanth *et al.*, 2017). Similarly, TiO_2 NPs were also synthesized by using root extract of *Acanthophyllum laxiusculum*. The plant genus *Acanthophyllum* is rich in non-ionic surface agents known as saponins. FTIR revealed the lack of surfactant templates to synthesize NPs, surface area and pore size distribution is evaluated from BET technique and BHJ model and UV- Visible confirmed the optical band gap of TiO_2 nanospheres (Madadi and Bagheri Lotfabad, 2016). Similarly, Abdul Jalill *et al.* (2016) reported the synthesis of TiO_2 NPs using *Curcuma longa* extract to study their antifungal and anti-pathogenic activity with concentration of 200 mg/ml inhibition against *F. graminearum* fungi . They also outlined the effect of synthesized NPs on germination parameters of *T. aestivum*.

Preparation of Plant Extracts

Fresh leaves are properly washed before being finely chopped, then placed in suitable solvents

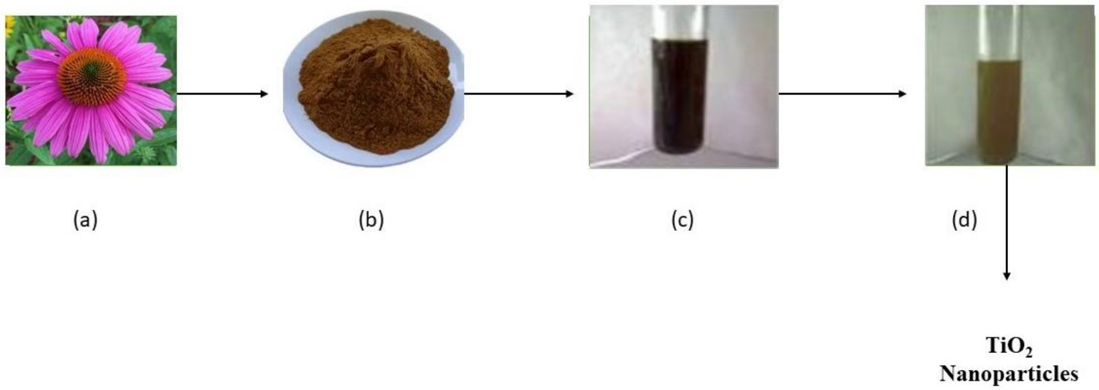

Fig. 1: Green synthesis of TiO_2 NPs using extract of *E. purpurea* herb, (a) *E. purpurea* flower (b) Extract of *E. purpurea* flower (c) plant extract solution (d) plant extract with 1 mM TiO_2 (adopted from Dobrucka, 2017).

like distilled water or ethanol and heated until the plant extract is ready to use. Due to heating the bioactive compounds present in leaves were breakdown thermally and they can be employed as reducing as well as capping agent (Dobrucka, 2017).

Titanium Dioxide (TiO_2) NPs

TiO_2 NPs may be synthesized from a variety of precursors, including titanium tetra isopropoxide (TTIP), titanium chloride ($TiCl_4$), titanium oxysulphate ($TiOSO_4$), etc. The ethanol or distilled water used to dissolve the bulk TiO_2 particles depends on the application. Then, drop by drop, the prepared plant extract is incorporated into the mixture. Following that, the solution was continually stirred at the proper temperature. The colour of the solution changes when NPs begin to appear as shown in Figure 1. The resulting NPs are then calcined, dried, and cleaned with distilled water. In order to eliminate extra organic groups, the synthesised NPs are placed in a furnace and heated to temperatures between 400 and 800 °C (Rao *et al.*, 2014; Thamima and Karuppuchamy, 2015).

Application of TiO_2 NPs using plant extracts

The utilization of materials in green synthesis of TiO_2 NPs such as plant extracts (seed, flower, peel, leaf, etc.) provides compatibility and eco-friendly behaviour for biomedical, optoelectronics and many other applications as they curtail the use of hazardous and noxious chemicals. They also possess great photocatalytic properties that intrigued greatly in waste water treatment. The harmful as well as organic contaminants present in the water, such as bacteria, viruses, and other dormant microorganisms, are degraded by the reactive superoxide and hydroxyl radicals produced by TiO_2 under UV radiation (Saif *et al.*, 2016). In this review, we aim to outline some potential applications which utilize biogenic TiO_2 NPs using plant-based materials as listed in Tables 1-5.

Antibacterial application

Several investigations on the antibacterial properties of biosynthesized TiO_2 NPs by employing different plant extracts, such as leaf, seed, stem, and flower parts, have been reported. For example, Hariharan *et al.* (2017) reported great antibacterial activity against gram-negative bacteria disclosed from green synthesis of TiO_2 NPs using leaf extract of *Cynodon dactylon* by agar wall diffusion method. They reported that as the TiO_2 concentration increases the bacterial activity also increases. Kumar *et al*. (2014) used *Hibiscus* flowers to synthesize TiO_2 NPs which were efficient for antibacterial activity due to its enhanced stability and dispersibility. Swathi *et al.* (2019) investigated that when biosynthesized TiO2 is produced by *Cassia fistula*, it exhibits excellent antibacterial action against pathogenic strains of *E. coli* and *S. aureus*. In addition, Farook *et al.* (2017) reported eco-friendly biosynthesis of titanium nanoparticles using *Citrus limon* leaf extract which displayed interesting results showing that irregular-shaped nanoparticles can inhibit *Escherichia coli* growth even at low concentrations, while Ampicillin served as a positive control and had only mild growth-inhibitory effects on *Pseudomonas aeruginosa*. Due to the existence of hydroxyl bonds, the acquired result was thought to be effective against clinical pathogens and may be employed further in antibiotic medications.

Photocatalytic application

The conduction band is separated from the valence band and has an empty energy level, whereas the valence band is filled with electrons and has a complete energy level. An electron from the valence band is transferred into a hole which are vacant in the conduction band hence, TiO_2 NPs absorbs UV light and gives photocatalytic activity. Reactive oxygen species (ROS), hydroxyl radicals, and superoxide ions are produced when conduction band electrons and valence band holes are combined with water and oxygen (Jacoby *et al.*, 1998; Blake *et al.*, 1999; Allahverdiyev *et al.*, 2011). Several investigations on photocatalytic activity of biogenic TiO_2 NPs by employing different plant extracts have been reported. For example, Sagadevan *et al.* (2021) studied the optical properties of green synthesized titanium oxide NPs using *Myristica fragrans* seed extract which indicates the blue shift and a band gap of 3.34 eV. The photocatalytic inefficacy synthesized NPs was also confirmed against the degradation of Methylene blue and Congo red dyes (Sagadevan *et al.*, 2021). Ahamad *et al.* (2021), reported the presence of different functional groups present on the surface of titanium oxide NPs which was synthesized eco-friendly with *Aegle marmelos* leaf extract. Photocatalytic degradation activity was also tested against nitroimidazole derivative drug ornidazole (Ahmad *et al.*, 2021). Sreekanth *et al.* (2017) reported a hexagonal and rectangular morphology in nanostructured titanium oxide produced by *Rhizoma coptidis* root extract and demonstrated photocatalytic activity towards the degradation of methylene blue and malachite green dyes under UV light and in the absence of light (Sreekanth *et al.*,2017).

Future challenges

The "biogenic synthesis" refers the development of eco-friendly and viable methods for producing NPs without using toxic chemicals. Despite great progress in this area, the researchers may face several challenges in future. One of the primary challenges is to scale-up the productions of TiO_2 NPs and to investigate various ways to enhance its efficiency. The utilisation of natural sources or plant extracts might contaminate the final outcome. To maintain the quality of TiO_2 NPs the impurities must be minimised and controlled. Apart from this, very few plants were employed in the Plant-based synthesis of TiO_2 NPs, and further study is vitally required in this field. There are many other additional constraints that must be overcome before they are taken into considerations, such as the structure, control of shape, size, monodispersed, and crystallinity of plant-mediated NPs. Subsequently, future challenges will entail to figure out how to trade on the similar biological techniques to build various forms including triangular, cuboidal, truncated, ellipsoidal, pyramidal, and oval. The morphology of NPs is also influenced by other parameters such as metal ion concentration, reaction temperature, plant extract concentration, and pH. Another challenge for TiO_2 NPs is to control the stability and agglomeration by reducing the surface area and reactivity so that their morphology does not alter and hence they can remain stable for a long time. There are few more obstacles to overcome such as photocatalytic efficiency, cost-effectiveness, integration with other materials, understanding the complex mechanisms and environmental impact.

Conclusion

In this review, the recent work on the green synthesis of TiO_2 NPs using various plant components like root, flowers, leaves, seed, stem etc. has been discussed. In addition, the mechanisms of their absorption, translocation, and accumulation in plants were investigated. The bio-synthesis is promoted due to noteworthy advantages which might be leveraged to control the size, shape, and crystalline structure by altering experimental parameters. Due to existence of phyto-molecules, plants have been considered to possess an exceptional efficiency as reducing, capping, and stabilizing agents for the synthesis of NPs with desired morphology. This review delivers an outstanding insight for people of scientific community like, researchers and beginners to gain diverse information on bio-synthesis of TiO_2 via plant extracts, continuing and broadening the scope of nature's potential as well as the advancement of effective and sustainable methodologies for nanoparticle synthesis with desirable traits.

Conflict of Interest

The authors declare no conflicts of interest.

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