The current trends in the green syntheses of titanium oxide nanoparticles and their applications

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ABSTRACT
Nanotechnology is a new star in the science horizon with many valuable applications and promises to offer. It includes the synthesis and utilization of nanostructure materials ranging from 1 to 100 nm. Mostly these materials are generally (or “could be”) produced via the laborious and hazard-prone physical and chemical methods but the green synthesis approaches easier, safer and scalable have been recently developed. Among other metal oxides nanoparticles, Titanium oxide (TiO2) nanoparticles have been mostly exploited for their photocatalytic, antimicrobial and antiparasitic applications. A diverse set of biological entities are used to reduce the precursor metal salt into respective nanoparticles. The secondary metabolites present in organisms such as plants or microbes are involved in the bio-reduction and capping processes. This article will provide an overview of the green synthesis of TiO2 NPs from different biological extracts such as plants, microbes and biological products as well as their potential applications.

ARTICLE HISTORY
Received 27 October 2017
Accepted 16 October 2018

KEYWORDS
Titanium; nanoparticles; nanotechnology; antimicrobial; photocatalysis

1. Introduction
Nanotechnology is an emerging field that has got phenomenal interest in the last few decades. The word “nano” means small, 1 billionth part of a meter Hussain et al. (1). The smaller size and unique surface chemistry of these nanostructures have been already exploited in medicine, nutrition, and energy Chandran et al. (2). Amongst other nanoparticles Titanium Oxide nanoparticles also exhibit unique surface chemistry and morphologies. It is used in synthesis of tints, textiles, papers, plastics, cosmetics, and foodstuffs Muhd Julkapli et al. (3). Colloidal TiO2 NPs are used in degradation of toxic chemicals in water Centi et al. (4). Pirkanniemi and Sillanpää (5). Mostly TiO2 NPs are produced via physico-chemical methods like chemical vapor deposition, micro emulsion, chemical precipitation, hydrothermal crystallization, and sol–gel methods Muhd Julkapli and colleagues (3), Valencia et al. (6). All these methods require high temperature, pressure and toxic chemicals which limits their production and potential medical uses Chen et al. (7). Hence, an eco-friendly and cost-effective approach is needed to synthesize these nanosized materials on larger scale with lesser hazards Jayaseelan et al. (8). This could be possibly accomplished by using biological extracts as a reducing agent; the green synthesis approach. The same reducing agent can synthesize more...
than one type of metallic nanoparticle Edmundson et al. (9). Moreover, nanoparticles with better morphology and stability are also produced Suresh et al. (10), Bhainsa and D’souza (11), Song and Kim (12). Mostly water-soluble metabolites are involved in the reduction process. The bio-mediated \( \text{TiO}_2 \) NPs have many applications such as diseases diagnostics, treatment, and manufacturing of surgical tools, tissue engineering, imaging, sensing, energy production and agriculture Jayaseelan and colleagues (8), Dobrucka (13), Órdenes-Aenishanslins et al. (14). This mini-review describes a brief overview of the research on bio-mediated \( \text{TiO}_2 \) NPs from different plants, bacteria, fungi and other biological derivatives. Moreover, the potential applications of bio-mediated \( \text{TiO}_2 \) NPs are also here emphasized.

2. Green synthesis of \( \text{TiO}_2 \) nanoparticles from different sources

In attempt to develop a cost effective, eco-friendly and energy efficient approach, researchers have exploited the potential of biological resources for the synthesis of \( \text{TiO}_2 \) NP Pantidos and Horsfall (15). The complete biosynthesis process as shown in Figure 1, a simple precursor salt is mixed with biological extract; the metabolites present in the extract can then reduce and stabilize the bulk metal into elemental form following various mechanical steps. This biosynthetic approach offers many advantages and has emerged as a simple, safe and feasible substitute to chemical and physical methods Nadeem et al. (16), Asha et al. (17), Marimuthu et al. (18), Jalill et al. (19), Singh (20). Apart from these, biological approach can effectively catalyze the synthesis process at any scale and condition. Moreover, NPs with controlled size and shape can also be produced Bao et al. (21). Owing to these benefits, numerous researchers have intended to explore diverse species for their potential to synthesize \( \text{TiO}_2 \) NPs.

2.1. Plants

Among the studied biological species, plants are considered as one of the most suitable candidates for the synthesis of NPs as they are cost effective, safe and easily available Mittal et al. (22). A diverse array of compounds in plants (phenolic acids, alkaloids, proteins and among them enzymes, as well as carbohydrates) regulate through reduction and stabilization processes the synthesis of NPs Dobrucka (13). Numerous plants species have been used for synthesis of various shapes of \( \text{TiO}_2 \) NPs (Table 1). The reaction mixtures start vigorously when a precursor \( \text{TiO}_2 \) salt is adulterated with plant extract, color change indicates the first sign of synthesis that can then be confirmed afterwards by spectroscopic techniques. Several color indicators have been reported ranging from light green to dark green in the formation of \( \text{TiO}_2 \) NPs Dobrucka (13), Rajakumar et al. (23), Rajakumar et al. (24).

Majority of green synthesis studies have been conducted on leaves extracts, as it is a rich source of metabolites. Spherical \( \text{TiO}_2 \) NPs resulted when \( \text{Annona squamosa} \) L. was added to the aqueous solution of \( \text{TiO}_2 \) salt at room temperature Roopan et al. (29). Similarly, leaf extract of \( \text{Calotropis gigantea} \) (L.) Dryand. was reported to reduce \( \text{TiO}_2 \) to nanoparticles within 6 hours. This high bio-reduction potential was ascribed to the presence of primary amines containing in the extract. The bio-mediated \( \text{TiO}_2 \) NPs showed good acaricidal activity against the larvae of \( \text{Rhipicephalus microplus} \) and \( \text{Haemaphysalis bispinosa} \) Marimuthu and colleagues (18). \( \text{TiO}_2 \) NPs synthesized from aqueous leaf extract of medicinaly important plant \( \text{Catharanthus roseus} \) (L.) G.Don has been reported. The aliphatic alcohols and amines present in the extract contributed to synthesis of \( \text{TiO}_2 \) NPs. The particle size ranged between 25–110 nm with irregular morphologies Velayutham et al. (32). Bio-mediated \( \text{TiO}_2 \) NPs have also been obtained from \( \text{Morinda citrifolia} \) L. extracts. The resultant NPs were confirmed by EDX, FTIR, SEM and XRD Sundrarajan et al. (41). The average size revealed via SEM was 15 nm, FTIR spectral data showed the presence of anthraquinones and various phenolic compounds which are supposed to be active reactants for the reduction of \( \text{TiCl}_4 \) to \( \text{TiO}_2 \) NPs. \( \text{Moringa oleifera} \) Lam. leaf extract was used to synthesize 100 nm nanoparticles with different structures and having good wound healing potential Sivaranjani and Philominathan (42). \( \text{TiO}_2 \) NPs from \( \text{Hibiscus rosa-} \)

![Figure 1. Reduction mechanism of TiO₂ NPs.](image-url)
WP: Whole plant.

### Table 1. TiO$_2$ nanoparticles synthesized from different plants species.

| S.no | Plant taxa                                      | Part used | Shape       | Size (nm) | Characterization          | Ref                        |
|------|------------------------------------------------|-----------|-------------|-----------|--------------------------|----------------------------|
| 1    | *Acanthophyllum laxissimum* Schiman-Czeika      | Roots     | Spherical   | 20-25     | XRD, FTIR, EDAX and TEM   | Madadi and Lotfabad (25)   |
| 2    | *Ageratina altissima* (L.) R.M. King and H. Rob. | Leaves    | Spherical   | 60-100    | XRD, FTIR, and FSEM       | Ganesan et al. (26)        |
| 3    | *Aloe vera* (L.) Burm.f.                        | Leaves    | Irregular   | 60        | TEM, XRD, UV, TGA and PSA | Rao and colleagues (27)    |
| 4    | *Annona squamosa* L.                           | WP        | Irregular   | 60-80     | XRD, PSA, SEM and FTIR    | Khadar et al. (28)         |
| 5    | *Anisomeles malabarica* (L.) R.B. ex Sims      | Leaves    | –           | 18        | XRD, SEM, TEM and EDS     | Roopan and colleagues (29) |
| 6    | *Azadirachta indica* A.Juss.                   | -         | Spherical   | 124       | UV and FTIR               | Sankar et al. (31)         |
| 7    | *Calotropis gigantea* (L.) Dryand.              | Flower    | Spherical   | 10        | SEM, EDX and XRD          | Marimuthu and colleagues (18)|
| 8    | *Catharanthus*                                 | Leaves    | Cluster     | 25        | XRD, FTIR and SEM         | Velayutham and colleagues (22)|
| 9    | *Cassia auriculata* (L.) Roxb.                  | Leaves    | Spherical   | 38        | UV, FTIR, FSEM and XRD    | Valli and Geetha (33)      |
| 10   | *Cicer arietinum* L.                            | Seeds     | Spherical   | 14        | TEM, XRD, UV and TGA      | Kasahle and colleagues (34) |
| 11   | *Cinnamomum tamala* (Buch.-Ham.) T. Nees and Ebern. | Leaves | –           | 8-20      | FESEM, TEM and FTIR       | Naik et al. (35)           |
| 12   | *Citrus sinensis* (L.) Osbeck                  | Peel      | Tetragonal  | 19        | TEM, XRD, TGA and PSA     | Rao et al. (36)            |
| 13   | *Curcuma longa* L.                             | WP        | –           | 50        | AFM, SEM, XRD and UV      | Jallil and colleagues (19) |
| 14   | *Gynodon Dactylon* (L.) Pers.                  | Leaves    | Hexagonal   | 13-34     | XRD, FTIR and SEM         | Sahu et al. (37)           |
| 15   | *Dandelion*                                    | Pollen    | Rod         | –         | XRD, FSEM and TEM         | Bao and colleagues (21)    |
| 16   | *Echinacea purpurea* (L.) Moench               | WP        | Polydisperse| 120       | TXRF, SEM and XRD         | Doeburcka (13)             |
| 17   | *Eclipta prostrata* L.                         | Leaves    | Spherical   | 36-68     | FTIR, XRD, AFM and FESEM  | Rajakumar and colleagues (23)|
| 18   | *Euphorbia prostrata* Aiton                    | Leaves    | Poly disperse| 83.22    | SAED, TEM and AFM         | Zahir et al. (38)          |
| 19   | *Hibiscus rosa-sinensis* L.                     | Flower    | Spherical   | 35        | FTIR, SEM and XRD         | Kumar and colleagues (39)  |
| 20   | *Jatropha curcas* L.                           | Latex     | Spherical   | 25-100    | SAED, EDAX, XRD and FTIR  | Hudilkar and colleagues (40)|
| 21   | *Marinda citrifolia* L.                        | Leaves    | Spherical   | 15-19     | EDAX, FTIR, SEM and XRD   | Sundarajan and colleagues (41)|
| 22   | *Moringa oleifera* Lam.                       | Leaves    | Spherical   | 100       | UV and SEM                | Sivaranjani and Philominathan (42)|
| 23   | *Nyctanthes arbor-tristis* L.                  | Leaves    | Spherical   | 100       | SEM and PSA               | Sundarajan and Gowri (43)  |
| 24   | *Ocimum basilicum* L.                          | Leaves    | Hexagonal   | 50        | XRD, FTIR, SEM, TEM and EDAX | Jayasinghe et al. (44)   |
| 25   | *Piper betle* L.                               | Leaves    | Spherical   | 7         | FTIR, UV, XRD, and SEM    | Hunagund et al. (45)       |
| 26   | *Psidium guajava* L.                           | Leaves    | Spherical   | 32.58     | FESEM, XRD and SEM        | Santoshkumar and colleagues (46)|
| 27   | *Solanum tribolatum* L.                        | –         | Spherical   | 70        | FTIR, XRD, AFM and FESEM  | Rajakumar and colleagues (24)|
| 28   | *Vigna radiate* (L.) R. Wilczek               | Legume    | Oval        | –         | SEM and FTIR              | Chatterjee et al. (47)     |
| 29   | *Trigonella foenum-graecum* L.                  | Leaves    | Spherical   | 20-90     | FTIR, UV, XRD, HR-TEM and HR-SEM | Subhapriya and Gomathipriya (48)|

WP: Whole plant.

*sinensis* L. leaf extract showed high antimicrobial activity against both gram-negative and positive strains of bacteria Kumar et al. (39). *Nyctanthes* leaves extracts derived TiO$_2$ NPs had uniform spherical shape and ranged in size from about 100 to 510 nm. These NPs were found to have a significant pediculocidal, acaricidal, and larvicidal activity Sundarajan and Gowri (43). *Cicer arietinum* L. beans extract TiO$_2$ NPs (14 nm) have been synthesized, FTIR confirmed that the reduction is attributed to the presence of different phenolic compounds in the extract Kashale et al. (34). The variation in size and morphology observed among the reported studies is due to the influence of reaction temperature, time and source of plant Dobrucka (13), Roopan and colleagues (29). Thus, improvements can be established in these parameters as these aspects influence the synthesis mechanism. Furthermore, a wide propitious plant extracts are left to be explored for the synthesis of TiO$_2$ NPs.

#### 2.2. Microorganism-based synthesized NPs

Many microbial species have been exploited to synthesize metallic NPs Nadeem and colleagues (16). TiO$_2$ NPs with various shapes and sizes have been reported in recent years (Table 2). Bacterial extracts in this regard have also been utilized for the green synthesis of TiO$_2$ NPs. Similarly, like their plant counterparts, bacterial metabolites also play a crucial role in the bio-reduction and stabilization of TiO$_2$ NPs. Órdenes-Aenishanslins and colleagues (14) reported synthesis of TiO$_2$ NPs by using *Bacillus mycoides*, spherical NPs (40–60 nm) were observed and confirmed by UV, TEM, FTIR and DLS. TiO$_2$ NPs (28–54 nm) synthesized using *Aeromonas hydrophila* extract showed effective inhibitory activity against *Staphylococcus aureus* (33 mm inhibition zone) and *S. pyogenes* (31 mm inhibition zone) Jayaseelan and colleagues (8). Jha et al. (49) observed the biosynthesis of TiO$_2$ NPs by the bacterium *Lactobacillus* and proposed that these NPs were synthesized through the combined action of oxidoreductases and glucose at mild pH. However, owing to their potential pathogenicity and laborious process bacterial synthesis have fewer chances to be commercialized.

The use of fungi in synthesis of metallic NPs has got substantial attention as they offer certain benefits over bacterial synthesis Pantidos and Horsfall (15). Ease of
scaling up, easier extraction, large surface area and economic viability are significant advantages to consider Mukherjee et al. (61). Fungus mediated, TiO\textsubscript{2} NPs with various shapes and sizes have been reported in recent years as well (Table 2). Fungus have the intrinsic ability to reduce bulk salt to elemental or ionic state either via enzymes or metabolites (Figure 2). Extract of Aspergillus\textit{flavus} was reported to have capability of reducing TiO\textsubscript{2} ions to TiO\textsubscript{2} NPs. The NPs showed good antibacterial activity against \textit{E.coli} Rajakumar et al. (57). \textit{Saccharomyces cerevisia} extract has also been used to synthesize TiO\textsubscript{2} NPs (12.6 nm), FTIR results confirmed that the reduction was attributed to the quinines and membranes reductases present in cells Jha and colleagues (49). The surface chemistry and pH of culture media also play an important role in synthesis of TiO\textsubscript{2} NPs. Like bacteria, fungi mediated TiO\textsubscript{2} NPs also have safety drawbacks. However, the application of non-pathogenic strains will

\begin{table}[h]
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\begin{tabular}{|c|c|c|c|c|}
\hline
S.no & Bacterial species & Part used & Shape & Size (nm) & Characterization \\
\hline
1. & \textit{Aeromonas} hydrophila & Spherical & 40.50 & FTIR, XRD, FESEM and AFM & Jayaseelan and colleagues (8) \\
2. & \textit{Bacillus amyloliquefaciens} & Spherical & 22.1–97.2 & FTIR, XRD, SEM and EDAX & Khan and Fulekar (50) \\
3. & \textit{Bacillus mycoides} & Polydisperse & 40–60 & UV, TEM, DLS and FTIR & Ordenes-Aenishanslins and colleagues (14) \\
4. & \textit{Bacillus subtilis} & Spherical & 30–40 & UV and TEM & Singh (20) \\
5. & \textit{Bacillus subtilis} & Spherical & 66–77 & UV, XRD, FTIR, AFM and SEM & Kirthi et al. (51) \\
6. & \textit{Bacillus subtilis} & Spherical & 10–30 & FTIR, UV, XRD and TEM. & Dhandapani et al. (52) \\
7. & \textit{Lactobacillus} & Spherical & 24.63 & XRD and TEM & Jha and colleagues (49) \\
8. & \textit{Lactobacillus} & Spherical & 40–60 & TEM and XRD & Prasad et al. (53) \\
9. & \textit{Planomicrobium} sp. & Spherical & 100 & XRD, FTIR and SEM & Malarkodi et al. (54) \\
10. & \textit{Aspergillus niger} & Spherical & 73.58 & XRD, SEM and UV & Durairaj et al. (55) \\
11. & \textit{Aspergillus tubingensis} & Spherical & <100 & AFM, EDS, SEM and TEM & Babitha and Korrapati (56) \\
12. & \textit{Aspergillus flavus} & Spherical & 62–74 & FTIR, XRD, AFM, SEM and TEM & Rajakumar and colleagues (57) \\
13. & \textit{Fusarium oxysporum} & Quasi-spherical & 9.8 & FTIR, TEM, XRD and XPS & Bansal et al. (58) \\
14. & \textit{Fusarium oxysporum} & Spherical & 10 & SAED, TEM, XRD and XPS & Bansal et al. (59) \\
15. & \textit{Aspergillus niger}, \textit{Rhizoctonia bataticola}, \textit{Aspergillus fumigatus}, and \textit{Aspergillus oryzae}. & & & & \\
\hline
\end{tabular}
\caption{TiO\textsubscript{2} nanoparticles synthesized from different microbial species.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fungus_mediated Biosynthesis of TiO2 nanoparticles.png}
\caption{Fungus mediated biosynthesis of TiO\textsubscript{2} nanoparticles.}
\end{figure}
wipe out the risk and could be used for commercial purposes.

2.3. Biological derivatives

Various biological derivatives as a green source for nanoparticle synthesis have also been utilized apart from micro and macro organisms Balasooriya et al. (62). However, only a few researchers have particularly explored the use of biological derivatives for biomimetic synthesis of TiO₂ nanoparticles. For instance, Farag et al. (63) utilized cellulose in order to synthesize TiO₂ nanoparticle having average size of 5–10 nm. The peptide R5, biological derivative of Cylindrothica fusiformis have also been exploited for the synthesis of TiO₂ nanoparticles Sewell and Wright (64). Titanium nano wires synthesized using alpha synuclein, a protein have been reported by Padalkar et al. (65). Bacterial flagella were used by Li et al 2012 as template for production of titanium nanotubes. The lignocellulose waste material derived from rice straw has also been utilized for the synthesis of TiO₂ nanoparticles Ramimoghadam et al. (66). Chen et al. (67) reported biomimetic synthesis to produce TiO₂ nanoparticles using different enzymes. Rutile TiO₂ nanoparticles were obtained when using glucose oxidase enzyme, catalase resulted in formation of anatase TiO₂ nanoparticles while lysozyme resulted in formation of monoclinic anatase TiO₂ nanoparticles Chen et al. (68). Some other notable biological derivatives used for biomimetic synthesis of TiO₂ nanoparticles are given in Table 3. In compassion with microbial-derived NPs, these derivatives based NPs are safe, cost efficient and scalable as well. Such NPs could be scaled for commercial applications including food and pharmaceuticals. Nevertheless, more studies should be carried out to address their safety/toxicity.

3. Applications of green TiO₂ NPs

Green mediated NPs have many applications in various fields of physical sciences, medicine and engineering technology Subhapriya and Gomathipriya (48). Though, biogenic TiO₂ NPs are studied for a lesser number of practical applications. However, results proclaim that these green synthesized NPs exhibit huge potential as compared to chemical and physical mode of synthesis. The most important application which is widely exploited is their incredible photocatalytic activity to clean contaminated water and eliminate environmental pollutants Sankar and colleagues (31), Pelaez et al. (78). It also exhibits a vast application in field of electronics, energy production, making of batteries and sensors Ördenes-Aenishanslins and colleagues (14), Kashale and colleagues (34). The biomedical potential of green mediated TiO₂ NPs have also been exploited, the main stream application includes photodynamic cancer treatment, antileishmanial agent and antimicrobial therapies Rajakumar and colleagues (57), Sahu and colleagues (37), Zahir and colleagues (38). The latter sections of the present review highlights, the most exploited biomedical applications with mechanistic approaches.

3.1. Antimicrobial potential

In literature, different metallic NPs have been used against various strains of bacteria Nadeem and colleagues (16). Similarly, TiO₂ NPs also exhibit eco-friendly biocidal properties, which are attributed to their strong oxidizing potential. These NPs have been used against a wide range of infectious microbes including various bacterial strains, endospores, fungi, algae, protozoa, viruses, microbial toxins and prions Visai et al. (79). TiO₂ NPs trigger the onset of reactive oxygen species (ROS) when confronted with microbial cells Jayaseelan and colleagues (8). These ROS kill microbes by disrupting cell wall’s integrity mainly by phospholipids oxidation, which results in reduced adhesion and distorted ionic balance. Inside the cytosol, it inhibits the respiratory cytosolic enzymes and modifying macromolecules structures, producing substantial effects on cellular integrity and gene expression. Furthermore, it also decreases the phosphate uptake and cellular communication.

Table 3. TiO₂ nanoparticles synthesized from biological derivatives.

| S.no | Bio-products | Shape           | Size (nm) | Characterization | Ref                  |
|------|--------------|-----------------|-----------|------------------|----------------------|
| 1    | Albumin      | Spherical       | 50        | XRD, FSEM and TEM| Bao and colleagues  (21) |
| 2    | Egg shell    | Rod             | 10        | TGA UV, FTIR, XRD and HRTEM| Yang et al. (69) |
| 3    | Gelatin      | Spherical       | 15        | TEM, FTIR, XRD and EDAX| Bagheri et al. (70) |
| 4    | Lignin cellulose | Irregular      | 13        | TGA UV, FTIR, XRD and TEM| Ramimoghadam and colleagues (66) |
| 5    | Starch       | Irregular       | 64–80     | XRD, UV, HRTEM and FESEM| Muniandy et al. (71) |
| 6    | Arginine     | Spherical       |           | SEM TEM EDX FTIR XRD XPS| Shi et al. (72) |
| 7    | Peptides     | Spherical       | 30–70     | SEM DLS EDX, XRD| Cole et al. (73) |
| 8    | Polyamine    | Hollow spheres | 3–4       | TEM XRD XPS| Yan et al. (74) |
| 9    | Lysozyme     | 50              | UV, XRD HR-TEM| KyeóKim and HyeokáPark (75) |
| 10   | Pomelo Peel  | 90              | UV-DRS, XRD, FTIR, SEM,| Zhang et al. (76) |
| 11   | Protamine    | Spherical       | 50        | SEM TEM FTIR XPS| Jiang et al. (77) |
across the cell Jayaseelan and colleagues (8), Kubacka et al. (80). A possible mechanism of action is described in Figure 3.

Both green synthesized and chemically derived TiO₂ NPs kill microbes in same fashion but the biologically derived NPs show better antibacterial activity. Their excellent antimicrobial potential is attributed to the capping agents provided by the plant extracts Kumar and colleagues (39). Morphology of NPs, membrane biochemistry and type of bacteria significantly affect antibacterial activity. Green synthesized TiO₂ NPs can efficiently inhibit both gram-positive and gram-negative bacteria, but due to comparative structural complexity of gram-negative bacterial cell wall, it is more reactive against gram-positive bacteria Marimuthu and colleagues (18). Some other studies of bio-mediated TiO₂ NPs tested against various stains of pathogens are presented in Table 4. The antimicrobial activity of bio-mediated TiO₂ NPs can be enhanced if irradiated with UV and fluorescent light Jayaseelan and colleagues (8), Roopan and colleagues (29). TiO₂ NPs Nano composites also exhibit enhanced antileishmanial activity, when green synthesized TiO₂ NPs were applied to Leishmanial cultures; lower cell viability, stunted growth and DNA fragmentation was observed Kubacka and colleagues (80). When compared to standard antibiotic disk TiO₂ NPs showed better antimicrobial activity Santhoshkumar and colleagues (46). Thus with such improved antimicrobial activity it considerably diminishes the occurrences for the development of antibiotic confrontation of pathogenic stains.

3.2. Anti-parasitic activities

Metallic nanoparticles have been effectively used against many species of parasitic larva and adult’s insects Benelli et al. (81). Green synthesized TiO₂ NPs have also been found to be effective larvicidal agents against various

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Table 4. TiO₂ nanoparticles synthesized from different microbial species.

| S.No | Source of synthesis | Microbes tested | Method used | Ref |
|------|---------------------|----------------|-------------|-----|
| 1.   | Aspergillus flavus  | Shigella dysenteriae type I, Staphylococcus aureus, Citrobacter sp., Escherichia coli, Pseudomonas aeruginosa, Bacillus subtilis, Candida albicans and F. oxysporum | Agar diffusion | Rajakumar and colleagues (57) |
| 2.   | Planomicrobium sp.  | Bacillus subtilis, Klebsiella planticola | Agar plate | Malarkodi and colleagues (54) |
| 3.   | Bacillus subtilis   | E. coli | Luria broth agar | Singh (20) |
| 4.   | Aeromonas hydrophila | A. hydrophila, Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus, Streptococcus pyogenes and Enterococcus faecalis | Disk diffusion | Jayaseelan and colleagues (8) |
| 5.   | Euphorbia prostrata | Leishmania donovani | RPMI 1640 medium | Zahir and colleagues (8) |
| 6.   | Hibiscus rosa-sinensis L | Vibrio cholerae, Pseudomonas aeruginosa and Staphylococcus aureus | Mueller Hinton agar | Kumar and colleagues (39) |
| 7.   | M. citrifolia       | Staphylococcus aureus, Escherichia coli, Bacillus subtilis, Pseudomonas aeruginosa, Candida albicans, and Aspergillus niger | Agar diffusion | Sundrarajan and colleagues (41) |
| 8.   | Curcuma longa       | F. graminearum | PDA medium | Jalil and colleagues (19) |
| 9.   | Psidium guajava     | Staphylococcus aureus and Escherichia coli | Disk diffusion | Santhoshkumar and colleagues (46) |
| 10.  | Vigna radiate       | E. coli, Staphylococcus aureus, Serratia marcescens, Salmonella , Pseudomonas aeruginosa, Klebsiella pneumoniae, Enterobacter., Proteus mirabilis, and Shigella | Well-diffusion | Chatterjee and colleagues (47) |
| 11.  | Cynodon Dactylon    | E. coli | Disk diffusion | Sahu and colleagues (37) |
| 12.  | Trigonella foenum-graecum | Staphylococcus aureus, Enterococcus faecalis, Klebsiella pneumoniae, Streptococcus faecalis, Pseudomonas aeruginosa, Escherichia coli, Proteus vulgaris, Bacillus subtilis, Yersinia enterocolitica and Candida albicans | Disk diffusion | Subhapriya and Gomathipriya (48) |
species of parasitic insects as shown in Table 5. The subcellular events leading to death include decrease in the biochemical parameters involved in growth and development Durairaj and colleagues (55) (Figure 4). To date less has been revealed regarding the antiparasitic potential of TiO₂. However, it shows huge potential in making anti-insect lotions and ointments and many others features, which will be unveiled as the technology emerges.

### Table 5. List of larva species tested against TiO₂ NPs.

| S.no | Organism used | Parasites tested | Results | Ref |
|------|---------------|------------------|---------|-----|
| 1.   | Catharanthus H. maculate and B. ovis | LD₅₀ = 7.09 and 6.56 mg/L | Velayutham and colleagues (32) |
| 2.   | Calotropis gigantea (L) | Rhipicephalus microplus and Haemaphysalis bispinosa LC₅₀ = 24.63 mg/L | Marimuthu and colleagues (18) |
| 3.   | Solanum trilobatum L. | Diculus hamanus capitis, Hyalomma anatolicum and Anopheles subpictus LC₅₀ = 28.80, 24.01, and 1.94 mg/L | Rajakumar and colleagues (24) |
| 4.   | Aspergillus niger | Aedes aegypti LC₅₀ 90 8.4 and 14.9 mg/L | Durairaj and colleagues (55) |

3.3. **Photocatalytic activity**

Industrial and domestic effluents contain many hazardous pollutants such as toxic dyes and nitroarene compounds. Their low solubility and high stability makes them highly persistent and resulting in many threats to aquatic life Valentín et al. (82). Recently, the distinctive structures and high catalytic potential of metallic NPs have been exploited. Their large surface area makes them excellent heterogeneous catalysts Rodrigues et al. (83). Moreover, these nanostructure catalysts can be easily recovered and recycled reaction mixture. But the agglomeration and toxicity of these metallic nanoparticles remain a concern Hotze et al. (84), Park et al. (85). TiO₂ NPs have been used mostly in catalyzing various reactions, due to their benign properties, low toxicity, high stability, excellent photocatalytic potential and optical properties Shah et al. (86). The photocatalytic activity of green mediated TiO₂ NPs have been reported by various authors for reduction of various dyes and compounds Valencia and colleagues (6), Bao and colleagues (21), Sankar and colleagues (31), Muniandy and colleagues (71), KyuáKim and HyeokáPark (75), Pelaez and colleagues (78). Figure 5 shows a typical pathway of electron flow after the possible photo excitation. The photo excited electron
initiates a cascade of electron transfer chain which results in degradation of toxic compounds aided by oxidizing potential of phytochemicals of the extracts Ganesan and colleagues (26), Muniandy and colleagues (71), Pelaez and colleagues (78). When compared with chemical synthesized TiO$_2$, the green mediated NPs showed excellent photocatalytic potential. The reducing ability is dependent on plant species, type of dye and temperature Zahir and colleagues (38). For instance when doped with other NPs and composites it significantly improve the catalytic potential. Salomatina et al. (87). TiO$_2$ NPs exhibit an incredible photocatalytic activity as revealed by these results, but still the reducing phenomenon is not elucidated completely which must be assessed.

Conclusion

Nanostructures materials have triggered a considerable attention in every field of science. Though metallic nanoparticles are produced by physio chemical process, but their toxicity, cost and laborious synthesis have led scientists to devolop new approaches for designing nanostructures. The solution of this dilemma resulted in an easy, safe and scalable approach known as the green synthesis method. In this method a precursor metallic salts is reduced by the metabolites of the organism. Moreover, NPs with high yield and better morphologies are also obtained. In this review article, we have discussed the synthesis of titanium oxide nanoparticles from different biological sources (plants, microbes and related bio-products). Furthermore the applications of green mediated titanium oxide NPs have also been described. Though, Titanium NPs have been reported by many authors till now but the synthesis steps have to be better characterized and need to be elaborated further by the identification of the responsible compounds in the extracts, the optimization of different factors such as pH, temperature or the amount of precursor salt, and extract should be studied for optimal yield and stable NPs production at feasible commercial scale.

Disclosure statement

No potential conflict of interest was reported by the authors.

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