Antagonistic Activity of Biogenic TiO$_2$ Nanoparticles against Staphylococcus aureus and Escherichia coli

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Abstract

Nanobiotechnology is an emerging field of science that utilizes nanobased systems for various biotechnological and biomedical applications. The synthesis of metal and metal oxide nanoparticles has attracted considerable attention, as they have high surface area and high fraction of atoms which is responsible for their fascinating properties such as antimicrobial, magnetic, electronic and catalytic activity. The antibacterial activities of TiO$_2$ nanoparticles were studied in Staphylococcus aureus and Escherichia coli. Treatment of the bacterial cells with TiO$_2$ NP’s resulted in the leakage of reducing sugars, proteins and reduced the activity of the respiratory chain dehydrogenases. In conclusion, the combined results suggested that TiO$_2$ NP’s was found to damage the bacterial cell membrane and depress the activity of some vital enzymes which eventually led to the death of bacterial cells. Thus TiO$_2$ NP’s could be used as an effective antibacterial material in the burgeoning field of Nanomedicine research with tremendous prospects for the improvement of combating human pathogens.

Keywords

Antibacterial Activity, Escherichia coli, Staphylococcus aureus, TiO$_2$ nanoparticles.

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Introduction

Particles having one or more dimensions of the order of 100 nm or less are termed as “Nanoparticles”. They have attracted global attention due to their unusual and fascinating properties and applications advantageous over their bulk counterparts (Daniel and Astruc, 2004; Kato, 2011). Nanobiotechnology is an emerging field of science that utilizes nano based-systems for various biotechnological and biomedical applications (Ahmed and Sardar, 2013). Nanoparticles have a high specific surface area and a high fraction of surface atoms and they have been studied extensively because of their unique physicochemical characteristics including catalytic activity, optical properties, electronic properties, antibacterial properties and magnetic properties (Krolikowska et al., 2003; Catauro et al., 2004). Different types of nanoparticles can be synthesized by a large number of physical, chemical, biological, and hybrid methods (Luechinger et al., 2010; Liu et al., 2011). Although physical and chemical methods are more popular in the synthesis of
nanoparticles, the use of harsh environmental conditions and toxic chemicals greatly limits their biomedical applications (Li et al., 2011).

Nanoparticles produced by a biogenic enzymatic process are far superior, in several ways, to those particles produced by chemical methods. The biogenic approach for the synthesis of nanoparticles is thought to be clean, nontoxic and environmentally acceptable “green chemistry” procedure. Nanomedicine is a burgeoning field of research with tremendous prospects for the improvement of the diagnosis and treatment of human diseases (Li et al., 2011). Nanotechnology is expected to open new avenues to fight and prevent disease using atomic scale tailoring of materials. Recently it has been demonstrated that metal oxide nanoparticles exhibit excellent biocidal and biostatic action against Gram-positive and Gram-negative bacteria (Lopez Goerne et al., 2012). TiO$_2$ has three crystalline phases: anatase, rutile and brookite. Moreover TiO$_2$ nanoparticles possess interesting optical, dielectric, antimicrobial, antibacterial, chemical stability and catalytic properties which leads to industrial applications such as pigment, fillers, catalyst supports and photocatalyst (Sundrarajan and Gowri, 2011). Anatase has attracted much attention owing to its application in photovoltaic cells and photocatalysts and for its antimicrobial properties (Ahmed and Sardar, 2013).

Materials and Methods

Biogenic Approach for the Synthesis of TiO$_2$ Nanoparticle

Chemicals Used

TiO (OH)$_2$ (99.9 %) was procured from Sigma Aldrich Chemicals, Bangalore, India. All other regents used in the reaction were of analytical grade with maximum purity. Deionized water was used throughout the experiment. The glass wares were washed in dilute nitric acid and thoroughly washed with double distilled water and dried in hot air oven.

Bacterial Strain Used

The bacterial strain used in this study was isolated from sludge and effluents were collected from textile and tannery industries. Based on the morphological, cultural, biochemical characteristics and 16 s rDNA sequencing, the isolate was identified as Staphylococcus arlettae. The pure cultures were maintained on nutrient agar slants at 4°C.

Synthesis of TiO$_2$ Nanoparticles

Staphylococcus arlettae strain IDR-4 cells were allowed to grow as broth culture for 1 week at 37°C in shaking condition at 120 rpm and were treated as source culture. 50 ml of the cultural broth was taken and centrifuged at 8000 rpm for 10 minutes. Following centrifugation, 20 ml of the culture supernatant was mixed with 20 ml of 0.025M TiO(OH)$_2$ to form a ratio of 1:1. The mixture was treated at 80°C for 10–20 min until white deposition starts to appear at the bottom of the flask, indicating the initiation of transformation. The culture solution was cooled and allowed to incubate at room temperature in the laboratory ambience. After
12–48 h, the culture solution was observed to have distinctly markable coalescent white clusters deposited at the bottom of the flask (Kirthi et al., 2011; Tharanya et al., 2015).

**Antibacterial activity of TiO₂ Nanoparticles**

The antibacterial effect of TiO₂ nanoparticles were examined by disc diffusion method against gram positive bacteria (*Staphylococcus aureus* and *Bacillus subtilis*) gram negative bacteria (*Escherichia coli* and *Serratia marcescens*) collected from lab stock.

Muller Hinton agar was prepared and poured onto the sterile petriplates. After solidification, 2 wells were cut (for test and control) and each culture was swabbed individually on the respective plates. The synthesized TiO₂ nanoparticles were diluted with distilled water (15μg/ml) and placed onto each wells and incubated for 24 hours. Following incubation the zone of inhibition against nanoparticle were observed and measured (Yokeshbabu et al., 2013).

**Assay the minimum inhibitory concentration of TiO₂ NP’s**

The minimum inhibitory concentration (MIC) of TiO₂ NP’s was determined by using the standard plate count method. The powdered form of TiO₂ NP’s was sterilized with UV radiation for 1 h, and the weighed under aseptic conditions. Mueller-Hinton broth containing 10⁵ CFU/ml of bacterial cells was used as a starter culture. Various concentrations of TiO₂ NPs (0, 50, 100, 150 and 200 μg/ml) was inoculated onto the above mentioned starter cultures and incubated in a shaking incubator at 37⁰C for 24 h. Following incubation, 100 μl of the test cultures was spread onto Muller-Hinton agar and incubated at 37⁰ C for 24 h. After incubation, the number of colonies grown on the agar was counted (Wang et al., 2006; Kim et al., 2011).

**Growth curve Determination of bacteria exposed to different concentrations of TiO₂ NP’s**

To investigate the antibacterial efficacy of TiO₂ NP’s, the growth curve of bacterial cells exposed to different concentrations of TiO₂ NP’s was taken. Mueller-Hinton broth with different concentrations of TiO₂ NP’s powder (0, 50, 100, and 150 μg/ml) was prepared, and the test bacterial culture (10⁵ CFU/ml) was inoculated and incubated in a shaking incubator at 37⁰ C for 24 h. Growth curve of bacterial culture were attained through repeated measures of the optical density (O.D) at 600 nm.

**Effect of TiO₂ NP’s on leakage of reducing sugars and proteins through membrane**

To investigate the leakage of reducing sugars and proteins through the host cell membrane, different volumes of Mueller-Hinton medium, TiO₂ NP’s and the test bacterial cells were added into 10 ml cultures with final concentration of 100 μg/ml TiO₂ NP’s and 10⁵ cfu/ml bacterial cells. Control experiments were performed in the absence of TiO₂ NP’s. The cultures were incubated at 37°C with shaking at 150 rpm. Following 4 h incubation, 1 ml of the bacterial cultures was sampled and centrifuged at 12,000 rpm, the supernatant liquid was frozen at -30°C immediately and then the concentration of reducing sugars and proteins were determined as soon as possible (Bradford, 1976; Miller, 1959).

**Assay the effect of TiO₂ NP’s on respiratory chain LDH activity in bacterial cells**

The dehydrogenase activity was determined according to previous iodonitrotetrazolium chloride method (Kim et al., 2009). The bacterial respiratory chain dehydrogenase will reduce colorless INT to a dark red water-
insoluble iodonitrotetrazolium formazan (INF). Different volumes of MH medium, TiO$_2$ NP’s and bacterial cells were added into 10 ml cultures. The bacterial cells were boiled for 20 min to inactivate the enzymes completely as the negative control, while the cells were not boiled, and their enzymes maintained native activity as the positive control. 1 ml culture was sampled and centrifuged at 12,000 rpm, then the supernatants were discarded and the bacteria washed by phosphate-buffered saline (PBS) twice and added 0.9 ml PBS to suspend the bacteria. INT solution (0.1 ml 0.5%) was added, the culture was incubated at 37°C in dark for 2 h, and then 50 μl formaldehyde was added to terminate the reaction. The culture was centrifuged to collect the bacteria and 250 μl solutions of acetone and ethanol 1:1 in volume were used to distill the INF twice. The supernatants were finally combined. The dehydrogenase activity was calculated according to the maximum spectrophotometrical absorbance of INF at 490 nm (Li et al., 2010).

Results and Discussion

Nanotechnology is regarded as a key technology which will have economic, social and ecological implication. The field of nanotechnology is one of the most active areas of research in modern materials science. Nanoparticles exhibit completely new or improved properties based on specific characteristics such as size, distribution and morphology. New applications of nanoparticles and nanomaterials are emerging rapidly. Nanotechnology is currently employed as a tool to explore the darkest avenues of antibacterials (Shoba et al., 2010).

Biogenic synthesis of TiO$_2$ nanoparticles using the culture supernatant of IDR-4

The bacterial strain used in this study was isolated from Environmental samples including sludge and effluents were collected from textile and tannery industries located in and around Kanchipuram, Tamil Nadu. The culture supernatant of the bacterial strain possessed the ability to mediate the biosynthesis of TiO$_2$ nanoparticles, which was apparent by the color change from golden yellow to dark white (precipitated at the bottom of the culture broth) after 24 h of incubation. Similarly titanium oxide nanoparticles were found to be synthesized by using Planomicrobium sp. (Malarkodi et al., 2013) and Chromohalobacter salaxigens (Tharanya et al., 2015). By 16 S r DNA analysis, the isolate IDR-4 was identified as Staphylococcus arlettae strain IDR-4.

Antibacterial activity of TiO$_2$ nanoparticles

The antibacterial activity of the biogenic TiO$_2$ nanoparticles were carried out against Gram positive (Staphylococcus aureus, Bacillus subtilis) and Gram negative (Escherichia coli Serratia marcescens) bacterial strains. TiO$_2$ nanoparticles exhibited maximum antagonistic activity on E. coli (16 mm) and S. aureus (13 mm).

The formation of zone around the TiO$_2$ nanoparticles well’s clearly proved the antibacterial property of TiO$_2$ nanoparticles. However, Bacillus subtilis and Serratia marcescens showed remarkable resistance against TiO$_2$. Further studies were carried out with the susceptible isolates - Escherichia coli and Staphylococcus aureus (Table 1).

The differential sensitivity of Gram-negative and Gram-positive bacteria towards nanoparticles may be depends upon their cell outer layer attribute and their interaction with the charged TiO$_2$ nanoparticles. It was observed that the negative charge on the cell surface of Gram-negative bacteria was higher than that the Gram-positive bacteria (Roy et al., 2010).
Growth curves of bacterial cells treated with different concentrations of TiO$_2$ NP’s

The growth curves of *S. aureus* and *E. coli* cells treated with TiO$_2$ NP’s indicated the suppression of the bacterial growth and reproduction of bacterial cells. In control group (cells not treated with TiO$_2$ NP’s), bacterial growth increased gradually with the increase in incubation time. However, the cells treated with TiO$_2$ NP’s showed gradual decline in their growth curve with increase in the incubation time and increase in the concentration of NPs. When treated in the presence of 150 μg/ml TiO$_2$ NP’s the growth of *S. aureus* and *E. coli* cells were found to be completely inhibited (Fig 1 and 2). Interestingly, upon comparison of the bacterial growth curves of *S. aureus* and *E. coli* cells, TiO$_2$ NP’s exhibited significant growth inhibition of *E. coli* than of *S. aureus*. Similar results were reported by Kim et al., (2011).

Minimum inhibitory concentration of TiO$_2$ NP’s

The minimum inhibitory concentration (MIC) was evaluated to determine the lowest concentration of the TiO$_2$ NP’s that could completely inhibit the viability of the *S. aureus* and *E. coli* cells. The viability of bacterial cells gradually decreased with the increase in the concentration of TiO$_2$ NPs. The MIC of TiO$_2$ NP’s against *S. aureus* and *E. coli* was found to be 150 μg/ml, at which the growth of both the bacterial strains was completely inhibited. The antibacterial activities of the TiO$_2$ NP’s against the Gram-positive *S. aureus* and Gram negative *E. coli* were almost identical (Fig 3 and 4). Similarly, TiO$_2$ nanoparticles biosynthesized by using the culture supernatant of *Planomicrobium* sp. exhibited remarkable antagonistic activity against *Bacillus subtilis* and *Klebsiella planticola* respectively (Malarkodi et al., 2013).

Table 1 Antibacterial activity of biogenic TiO$_2$ NP’s against the selected bacterial isolates

<table>
<thead>
<tr>
<th>S. No</th>
<th>Bacterial strains</th>
<th>Zone of Inhibition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><em>Staphylococcus aureus</em></td>
<td>13 ± 0.5 mm</td>
</tr>
<tr>
<td>2.</td>
<td><em>Bacillus subtilis</em></td>
<td>6 ± 0.4 mm</td>
</tr>
<tr>
<td>3.</td>
<td><em>Serratia marcescens</em></td>
<td>7 ± 0.6 mm</td>
</tr>
<tr>
<td>4.</td>
<td><em>Escherichia coli</em></td>
<td>16 ± 0.8 mm</td>
</tr>
</tbody>
</table>

Fig.1 Growth curve of *Staphylococcus aureus* in the presence of TiO$_2$ nanoparticles
Fig. 2 Growth curve of *Escherichia coli* in the presence of TiO\(_2\) nanoparticles

![Graph showing growth curve of Escherichia coli](image1)

Fig. 3 Minimum Inhibitory Concentration of TiO\(_2\) NP’s on *Staphylococcus aureus*

![Graph showing minimum inhibitory concentration](image2)

Fig. 4 Minimum Inhibitory Concentration of TiO\(_2\) NP’s on *Escherichia coli*

![Graph showing minimum inhibitory concentration](image3)
**Fig. 5** Effect of TiO$_2$ NP’s on protein leakage from *Staphylococcus aureus* cells

**Fig. 6** Effect of TiO$_2$ NP’s on protein leakage from *Escherichia coli* cells

**Fig. 7** Effect of TiO$_2$ NP’s on leakage of reducing sugars from *Staphylococcus aureus* cells
Fig. 8 Effect of TiO$_2$ NP’s on leakage of reducing sugars from *Escherichia coli* cells

![Graph showing the effect of TiO$_2$ NP’s on leakage of reducing sugars from *Escherichia coli* cells.]

Fig. 9 Effect of TiO$_2$ NP’s on the activity of Respiratory Chain Dehydrogenases in *Staphylococcus aureus* cells

![Graph showing the activity of Respiratory Chain Dehydrogenases in *Staphylococcus aureus* cells.]

Fig. 10 Effect of TiO$_2$ NP’s on the activity of Respiratory Chain Dehydrogenases in *Escherichia coli* cells

![Graph showing the activity of Respiratory Chain Dehydrogenases in *Escherichia coli* cells.]

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Effect of TiO$_2$ NP’s on protein leakage from bacterial cell membranes

It was found that TiO$_2$ NPs could enhance the leakage of protein by elevating the membrane permeabilities of the susceptible bacterial cells. Initially, protein leakage from the membranes of control S. aureus cells (without TiO$_2$ NP’s treatment) and test S. aureus cells (treated with TiO$_2$ NP’s) remained almost the same (10.24 and 12.12 μg/mg respectively). After 4 h incubation, protein leakage from S. aureus cells treated with TiO$_2$ NP’s considerably increased (18.52 μg/mg); however, the protein leakage from cells in the control group was found to be 12.22 μg/mg (Fig 5). Similarly, TiO$_2$ NP’s also increased the leakage of proteins through the membrane of E. coli. At start time (0 h), the leakage of proteins from cells in control experiment was 12.22 μg/mg, while leakage of proteins from cells treated with TiO$_2$ NPs was 14.08 μg/mg. The leakage of proteins in E. coli treated with TiO$_2$ NP’s for 4 h was found to be 19.06 μg/mg, in contrast the protein liberation from control experiment was found to be 12.24 μg/mg (Fig 6).

Effect of TiO$_2$ NP’s on the membrane leakage of reducing sugars

Fig 7 and 8 revealed that TiO$_2$ NP’s could elevate the leakage of reducing sugars from the bacterial cell membranes. At start point (0 h), only traceable amount of reducing sugars was found be leaked from S. aureus cells in control experiment, while the leakage amount of reducing sugars was found be 108.72 μg per mg, but the leakage was only 26.36 μg/mg in control cells. At start point (0 h), only traceable amount of reducing sugars was found be leaked from E. coli cells in control experiment, while the leakage amount of reducing sugars from E. coli cells treated with TiO$_2$ NP’s reached 32.12 μg per bacterial dry weight of 1 mg (μg/mg). After treatment with TiO$_2$ NP’s for 4 h, the leakage amount of reducing sugars was found to be 122.60 μg per mg, but the leakage was found to be 32.12 μg/mg in case of control cells.

Effect of TiO$_2$ NP’s on Respiratory Chain Dehydrogenases

In case of S. aureus control cells, the enzyme activity was found to be in increased with the increase in incubation time reaching the maximum of 148 μU/ml after 40 min of incubation. Interestingly, enzymatic activity of S. aureus cells treated with TiO$_2$ NP’s was found to be inversely proportional to the increase in incubation time (Fig 9). In case of E. coli control cells, the enzyme activity was found to be in increased with the increase in incubation time reaching the maximum of 322 μU/ml after 40 min of incubation. Interestingly, enzymatic activity of E. coli cells treated with TiO$_2$ NP’s was found to be inversely proportional to the increase in incubation time (i.e.) the initial enzyme activity at start time (40 µU/ml) was drastically reduced to 16 µU/ml after 40 min of incubation (Fig 10). According to Ahearn et al. (1995), nanoparticles can lead to enzyme inactivation via formatting complexes with electron donors containing sulfur, oxygen or nitrogen (thiols, carboxylates, phosphates, hydroxyl, amines, imidazoles, indoles). Nanoparticles may displace native metal cations from their usual binding sites in enzymes (Ghandour et al., 1988).

References


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