International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081 (Online)
An Online International Journal Available at http://www.cibtech.org/jgee.htm
2013 Vol.3 (3) September-December, pp.197-212/Sarayu and Sandhya
Review Article

ROLE OF CHEMICAL AND BIOLOGICAL NANOPARTICLES IN WATER DISINFECTION

Sarayu K.[1] and *Sandhya S.[2]
[1]*Structural Engineering Research Centre, Taramani, Chennai - 600 113*
[2]*National Environmental Engineering Research Institute, CSIR-Complex, Chennai - 600 113*
**Author for Correspondence*

ABSTRACT
Water is one of the important natural resource for human kind. Microbial and chemical contamination challenges the world in providing safe and clean water to the society. Nanotechnology can be used to synthesize photocatalyst of chemical and biological origin for the removal of micro-organisms. It has recently become an area of interest to researchers. This paper covers such applications for water decontamination, the basic processes involved in photocatalyst synthesis, the mechanism that executes the photocatalytic killing of microorganisms and examples of recent research into the use of photocatalysis for the removal of a range of microorganisms are detailed. This paper also presents the developments and the application of nanoparticles of biological origin in the field of disinfection. It elaborately describes the required needs for the development of a proper eco-friendly technology for the disinfection and the drawbacks in the existing technologies.

Key Words: *Disinfection, Microbicidal Mechanisms, Chemical Nanoparticles, Plant Nanoparticles, Microbial Nanoparticles*

INTRODUCTION

Nanoparticles in Disinfection

Water is most precious, demanding and the most essential natural resource on earth which is under serious threat due to the growing influx of microbial contamination and chemical pollution as a result of heavy industrialization and rising population. This has led to a great challenge in providing safe and clean water to the society eventhough there has been enough commercial, domestic and industrial scale water purification techniques available involving reverse osmosis (Bodalo-Santoyo *et al.,* 2003) and electrochemical processes (Chen and Schluesenera, 2008). The control of microbial contaminations by these methods is proven to be less effective. Chlorination has traditionally been the most extensively used technology for disinfection, but the harmful character of organo-chloro by-products has urged to find the alternative processes to easily achieve the disinfection of water and the removal of pollutants (WHO, 2008). The World Health Organization (WHO) has stated that microbial hazards are the primary concern for drinking water quality in both developed and underdeveloped countries. The greatest risk is associated with the consumption of water contaminated with human or animal feces as these are a source of pathogenic bacteria, viruses, fungi, protozoa and helminths. Therefore, the use of any technology which can improve the quality of drinking water will provide significant worldwide health benefits (Raveendran *et al.,* 2003).

AOPs (Advanced Oxidation Processes) generally work based on the in-situ generation of highly reactive transitory species (i.e. H_2O_2, OH^-, $O_{2,}$ ^-e, O_3) for the mineralization of organic compounds, water pathogens and disinfection by-products (Korbekandi *et al.,* 2009). Among these AOPs, the heterogeneous photocatalysis engaging semiconductor (nanoparticles) catalysts (TiO_2, ZnO, Fe_2O_3, CdS, GaP and ZnS) has been demonstrated by various researchers. Chong *et al.,* (2010) have described about the semiconductors efficiency in degrading a wide range of organics into readily biodegradable compounds. Malato *et al.,* (2001) have outlined the eventual mineralization of these compounds to innocuous carbon dioxide and water. In particular, the potential of nanoparticles to revolutionize century-old conventional water treatment processes have been enunciated recently (Zhang *et al.,* 2007). This article will focus on photocatalytic disinfection of microorganisms by explaining the recent developments and the mechanism driving the photocatalytic disinfection. It also concentrates in the recent findings for the real application of this technology to water treatment.

Process of Preparation

Nanoparticles are generally synthesized by physical and chemical methods of chemical and biological origin. The synthesis of capable nanoparticles is mainly based on two approaches namely the Bottom up approach (building from molecular size to large and complex systems) and the Top down approach (break down of complex to small nano molecules) (Figure 1). The commonly used physical, chemical and biological methods for the synthesis of nanoparticle are described in the Table 1.

The need for biosynthesis of nanoparticles arose with the heavy investments required for the physical and chemical processes.

So, scientists started using microorganisms and plant extracts for the synthesis of nanoparticles involving various processes which have contributed to the development of relatively new and largely unexplored area of research based on the biosynthesis of nano-materials (Huang *et al.,* 2000). Biosynthesis of nanoparticles is a kind of bottom up approach where the main reaction occurring is reduction/oxidation. The three main aspects to be noted in preparation of nanoparticles evaluated from a green chemistry perspective are the choice of the solvent used for the synthesis, the choice of a reducing agent and the choice of a material for the stabilization of the nanoparticles (Wu *et al.,* 2009). The important aspects to be considered in the process of preparing highly stable and well constructed bio-nanoparticles are

- Best microorganisms (Lu *et al.,* 2003).
- Factors affecting the reaction condition.

Mechanism of disinfection via antimicrobial activity of the chemical, physical and biological nanoparticles

Chemical Nanoparticles Mediated Killing

The photocatalytic disinfection of microorganism is based on a strong photo-oxidation process, where a photocatalyst in conjunction with the light source of appropriate wavelength is used (Matsunaga *et al.,* 1985).

Photocatalytic oxidation occurs when the light of certain photon energy is absorbed by the nano material which generates an electron-hole pair as the electron from the valance band is transferred to the conduction band by leaving a positively charged hole behind which generates a highly reactive hydroxyl (OH) radical and super oxide ions (highly oxidizing agents) to oxidize the cell membrane and destroy the microorganisms (Benabbou *et al.,* 2011). Hence the nano size and the band gap energy of the photocatalytic material play a crucial role in the enhancement of the photocatalytic process (Sontakke *et al.,* 2010).

These species are capable of producing oxidative stress on the microorganisms, by attacking the external cell wall that proceeds to the plasma membrane and then to the cytoplasm releasing the intracellular contents thus upsetting the balance of the vital functions which leads to death (Ryu *et al.,* 2008).

Wu *et al.,* (2009) used scanning electron microscopy to investigate the cell morphology of *E. coli* treated with a PdO/TiON photocatalyst and observed pit and holes on the surface.

Biological Nanoparticles Mediated Killing

Biological nanoparticles are prepared from biological molecules that have antibacterial activity. These particles are mostly comprised of enzymes and fine particles of nano size that are isolated from a biological sources like plants, algae, bacteria, fungus, actinomycetes etc.

These particles are generally combined or doped with metal ions like Au, Ag, Pl, Pt, ZnO etc. in such a way that it enhances the bactericidal activity of the whole compound. Their antibacterial activities could be interpreted by three factors: the metal nanoparticles themselves, the released metal ions and the generated reactive oxygen species (Zhu *et al.,* 2006).

Mechanism behind Cell Deconstruction

Extracellular Inactivation

It targets the damage of the peptidoglycan layer (Gram positive and Gram negative organisms), lipopolysaccharide layer (Gram negative organisms), phospholipids bilayer (Gram positive and Gram negative organisms).

Peptidoglycan Layer

It is a peptide cross linked polysaccharide matrix that constitutes to 90% of the cell wall in gram positive bacteria and 10% in gram negative bacteria. It is susceptible to the radical attack of the nanoparticle (Li *et al.,* 2005) and is very porous in nature thus can allow the passage of hydroxyl radicals and the super oxides (Zhao *et al.,* 2004) and can further attack the cell membrane. It is also well described by the researchers that these oxidative species can split up the peptidoglycan mesh formed of the N-acetylglucosamine and N-acetylmuramic acid bound to amino acids to monomers resulting in the deconstruction of the peptidoglycan layer and makes it highly perforated (Hamal and Klabunde, 2007) (Figure 2).

Lipopolysaccharide

Effect of reactive oxygen species on the cellular molecules has long been reported. The lipopolysaccharide layer of the cell undergoes lipid peroxidation when subjected to photocatalytic disinfection affecting the major subunit lipid A, which helps not only in the destruction of the lipopolysaccharide layer but also in the neutralization of the toxicity effect of the organism making it incapable (Vasant and Ghulam, 2009).

Phospholipid Bilayer

The reactive oxygen species attacks this layer mainly through a radical chain reaction which can cause cell injury at even distant sites from the point of initiation. The unsaturated fatty acids react with radicals in the presence of oxygen to form additional lipid radicals for further reaction (Li *et al.,* 2005). This chain reaction eventually leads to the oxidation of the bio-molecules throughout the cell (Franklin *et al.,* 2010). This eventual impact of the membrane peroxidation changes the cell permeability levels leading to disruption of the membrane releasing the cytoplasmic fluid (Franklin *et al.,* 2010) thus inhibiting the membrane mediated respiration.

Intracellular Inactivation

Cytoplasm consists of complex mixture of substances and structures that include DNA, RNA and ribosome with dissolved and suspended materials, which has a vital role in cell functioning. It was demonstrated that lipid radicals, hydrogen peroxide, super oxide and surface-bound radicals can attack the intracellular target sites (Li *et al.,* 2005; Franklin *et al.,* 2010). The hydroxyl radicals produced by the super oxides and the hydrogen peroxide in reaction with iron available in the intracellular environment can also contribute to the attack of enzymes, coenzymes and nucleic acids (Sondi and Salopek-Sondi, 2004).

Enzymes, Coenzymes and Nucleic Acid

Enzymes, the major constituents of the cytoplasm and can catalyze a variety of chemical reactions in the cell can be directly inactivated by the superoxides thus arresting the cell metabolism (Morones *et al.,* 2005). DNA which is highly susceptible for oxidation stress is attacked either at sugars or at base which undergoes fragmentation with base loss and strand breakage leading to terminal garmented sugar residues (Sondi and Salopek-Sondi, 2004).

Nanoparticles for Disinfection

The disinfection of water using photocatalysis has been shown by the destructive effects it has on a wide range of microorganisms like bacteria (Gogoi *et al.,* 2006), viruses (Brunner *et al.,* 2006), fungi (Rajesh *et al.,* 2010) and protozoa (Chandran *et al.,* 2006). It has been well understood that the effect of aeration, pH, chemical nature of the medium, type and concentration of photocatalyst, light intensity and treatment time are the crucial factors that influence the photocatalytic disinfection (Zheng *et al.,* 2010). At the same time consideration should be given to other factors like the nature of organisms targeted – cell wall complexity the Gram positive bacteria like *Enterococcus* sp. require a longer treatment time than gram negative bacteria such as coliforms (Dubey *et al.,* 2009) and protozoa being the more resistant to photocatalysis, followed by bacterial spores, mycobacteria, viruses, fungi and bacteria. Some pathogenic organisms can form spores which require longer treatment time for photocatalytic destruction (Duran *et al.,* 2007).

Chemical and Physical Nanoparticles

TiO_2

Large number of studies published in recent years has discussed the potential benefits of photocatalysis using TiO_2 for water treatment and air pollution control. High attention has been given to TiO_2 from very long back due to their high photocatalytic activity, biological and chemical inertness, stability, resistance to photo-corrosion, low cost, non-toxic nature and favorable band-gap energy (Qu *et al.,* 2011). Generally sol-gel method has been used for the preparation of ultrafine TiO_2-metaloxide particles. The antibacterial properties of TiO_2 photo-catalysis are due to the generation of reactive oxygen species of which hydroxyl radicals are considered to be the most important. The accepted sequence of events which take place when microorganisms undergo TiO_2 photocatalytic attack are thought to be cell wall damage followed by cytoplasmic membrane damage leading to a direct intracellular attack (Fu *et al.,* 1995) (Figure 3). TiO_2 when heated at high temperature gets transformed to rutile phase from anatase phase with band gap energy of 3.0 eV. They absorb photons from light source which leads to the shift in electrons from valence band to conduction band leaving positive holes in the valence band. However, these can recombine rapidly. This recombination of TiO_2 can be overcome by various process cited in the literature like ion implantation and chemical methods (Satyavani *et al.,* 2011). In context, a great deal of efforts has shown that doping with noble and transitory metals has prevented recombination, extending their spectral response to visible light and to acquire an enhanced photoreactivity (Singh *et al.,* 2011). Besides metal-ion doping, some reports have described the non-metal ion (carbon) (Holmes *et al.,* 1995), nitrogen (Klaus-Joerger *et al.,* 2001), phosphorus (Du *et al.,* 2007), sulfur (Husseiny *et al.,* 2007), fluorine (Jha and Prasad, 2009) and boron (Bansal *et al.,* 2004) doping system which will further narrow down the band gap (Hamal and Klaunde, 2007). Later, doping with combination of metals and non-metals were also tried as this could reproduce a TiO_2 with a very little band gap that results in effective killing of microorganisms.

Initially, researchers like Wu *et al.,* (2009) concentrated in doping TiO_2 with noble metals like Ag, Au, Pd, Pt etc. Later the interest shifted to Ag as it was affordable metal and has a high microbicidal activity (Sun *et al.,* 2010). Jain *et al.,* (2009) prepared Ag-TiO_2 nanofibres by electro-spinning method for the disinfection of microorganisms. Vasanth *et al.,* (2010) have demonstrated the disinfection of *E. coli* from artificially contaminated water with 4% weight of Ag in Ag- TiO_2 nanoparticle. Alrousan *et al.,* (2009) used immobilised nanoparticle TiO_2 films to show that deactivation rates of *E. coli* were significantly lower in surface water samples compared to distilled water. They found that the organic and inorganic content of surface water lead to a reduction in the rate of photocatalytic disinfection with the presence of humic acid. Lydakis-Simantiris *et al.,* (2010) examined the disinfection of natural spring water and secondary treated municipal wastewater by TiO_2 photocatalysis. They also identified the debris and excretions of the dead bacteria interfered in the reaction by reducing the light penetration. Leung *et al.,* (2008) investigated the susceptibility of mid-log, late-log and stationary phase cells of the marine bacteria *A. alvinellae* and *P. phosphoreum* to photocatalytic treatment. The use of solar irradiation to disinfect natural water sources enhances the attractiveness of this technology particularly for use in remote areas (Marugan *et al.,* 2010). The other modifications of TiO_2 mediated photocatalytic disinfection of microorganisms are clearly described in Table 2.

ZnO

ZnO has also been engaged in the production of sunscreens, coatings, and paints similar to TiO_2 due to its high capacity of UV absorption and transparency to visible light (Franklin *et al.,* 2010). They own a broad spectrum of antimicrobial activity against many organisms (Huang *et al.,* 2008). The mechanism behind the antibacterial activity of ZnO is still under investigation and is expected to follow the mechanism similar to that of TiO_2 with the generation of hydrogen peroxide. The unique property of ZnO nanoparticles to penetrate the cell envelope and to disorganize the bacterial membrane upon contact is also indicated to enhance their bactericidal activity in disinfection (Brayner *et al.,* 2006), but still the role of Zn^{2+} ion released from dissolution of ZnO is not clearly explained and understood (Franklin *et al.,* 2010). Some studies have suggested that Zn^{2+} ions generated bind to the membranes of microorganisms and helps in a prolonged lag phase of the microbial growth cycle (Atmaca *et al.,* 1998) which leads to the ultimate death of the cells (Table 2). The antimicrobial nature of the ZnO has been exploited but the mechanism of disinfection is still under study.

nAg

The antimicrobial properties of silver compounds and silver ions have been historically recognized and applied in a wide range of applications from disinfecting medical devices and home appliances to water treatment (Chou *et al.,* 2005; Yamanaka *et al.,* 2005). Eventhough, the mechanism of toxicity is still only partially understood it is clear that silver ions interact with thiol groups in proteins, resulting in inactivation of respiratory enzymes and leading to the production of ROS (Matsumura *et al.,* 2003). It was also shown that Agþ ions prevent DNA replication and affect the structure and permeability of the cell membrane (Feng *et al.,* 2000). Sondi and Salopek-Sondi (2004) have proposed that the nAg particles degrade the lipopolysaccharide molecule leading to pits formation which will in turn increase the membrane permeability, others have described that the nAg particles penetrate the cell and damage the DNA. The size of the nAg play a crucial role in their photocatalytic activity (Xu *et al.,* 2004) and Gogoi *et al.,* (2006) have described that nAg of size <10 nm are more toxic to *E. coli* and *Pseudomonas aeruginosa*. Castellano *et al.,* (2007) have described that metallic silver damages the bacterial cell wall and nuclear membrane when reacts with water. Silver zeolites made by complexing alkaline earth metal with crystal aluminosilicate were found to play a crucial role in disinfection and decontamination (Kawahara *et al.,* 2000; Matsumura *et al.,* 2003). Feng *et al.,* (2000) have well described the mechanism of bacterial inhibition using *S. aureus* and *E.coli*. Spacciapoli *et al.,* (2001) have demonstrated the use of silver for killing periodontal pathogens. Gong *et al.,* (2007) synthesized the bifunctional Fe_3O_4-Ag nanoparticles possessing super paramagenetic and antibacterial properties against *E. coli*, *S. epidermis* and *B. subtilis*. The bactericidal activity of silver nanoparticles against the pathogenic, MDR as well as multidrug susceptible strains of bacteria was studied by many scientists, and it was proved that the silver nanoparticles are the powerful weapons against the MDR bacteria such as *Pseudomonas aeruginosa*, ampicillin-resistant *Escherichia coli*, erythromycin-resistant *Streptococcus pyogenes*, methicillin-resistant *Staphylococcus aureus* (MRSA) and vancomycin-resistant *Staphylococcus aureus* (VRSA).

Other Chemical Nanoparticles

Many other materials like copper, zinc, platinum (Retchkiman-Schabes *et al.,* 2006), magnesium, gold (Gu *et al.,* 2003), alginate (Ahmad *et al.,* 2005) have been used for the preparation of nanomaterials that are effective disinfectants. Several compounds like SiO_2, CdS, ZrO_2, V_2O_5, CuO, Fe_2O_3, Al_2O_3 etc have been investigated as potential photocatalytic materials for use in water purification and disinfection (Table 2) (Parvulescu *et al.,* 2010; Murthy *et al.,* 2010; Sharma *et al.,* 2009). Pera-Titus *et al.,* (2004) have reported the significance of H_2O_2 in the subject of disinfection. Lanao *et al.,* (2012) have also used H_2O_2 and TiO_2/ H_2O_2 for disinfection and have found out that the TiO_2 had better effect than that of H_2O_2. Graphene oxide nanosheets impregnated with silver nanoparticles was used by Bao *et al.,* (2011) for disinfecting *S. aureus* and *E. coli*. Other researchers has also found that graphene oxide nanosheets impregnated with Au, TiO_2, ZnO, Fe_3O_4 was effective in disinfection process (Yang, 2001) . Silica nanoparticles have been used for the treatment of water and wastewater form long back (Benabbou *et al.,* 2011) .The antibacterial effect of tungsten trioxide was described by Gondal *et al.,* (2009) against *E. coli* present in water; he has also explained that a laser irradiation of 355 nm helped in the total disinfection of water with tungsten trioxide as catalyst Another major interest of researchers was Fe nanoparticles which has played an important role in water treatment and disinfection of water (Brunner *et al.,* 2006). Still research should be concentrated in finding an eminent, economic and simple nanoparticle for an easy disinfection of water for the society.

Biological Nanoparticles for Disinfection

Plant Nanoparticles

Biosynthesis of nanoparticles using biological materials like plants is currently under exploitation. The effect of plants, plant leaf and plant extracts on microorganisms have been studied by many researchers worldwide (Mathabe *et al.*, 2006). The process of green synthesis of nanoparticles is environmental friendly, easily scaled up to large volumes, devoid of high pressure, energy, temperature and toxic chemicals (Jain *et al.*, 2009). A number of plants are being studied now for the synthesis of nanoparticles using metals like Au, Ag, Indium oxide, Iron etc (Table 2). Green silver nanoparticles have been synthesized using various natural products like *Nelumbo nucifera* (Santhoshkumar *et al.*, 2011) and *Pongamia pinnata* (Rajesh *et al.*, 2010). *Musa paradisiacal* contains large amounts of dopamine and L-dopa, catecholamines was best studied for their antimicrobial activity (Table 3). There have been several reports on the synthesis of Ag-NPs using medicinal plants such as *Basella alba*, *Helianthus annus*, *Saccharum officinarum*, *Oryza sativa*, *Sorghum bicolour*, *Zea mays* (Leela and Vivekanandan, 2008), *Aloe vera* (Chandran *et al.*, 2006), *Medicago sativa* (Alfalfa) (Gardea-Torresdey *et al.*, 2003), *Capsicum annuum*, *Magnolia kobus* (Song *et al.*, 2009), *Cinnamomum camphora* leaf (Huang *et al.*, 2007), and *Geranium* sp. (Shankar *et al.*, 2004) for disinfection applications. The various plants and metals used for the preparation of nanoparticles are summarized in Table 2.

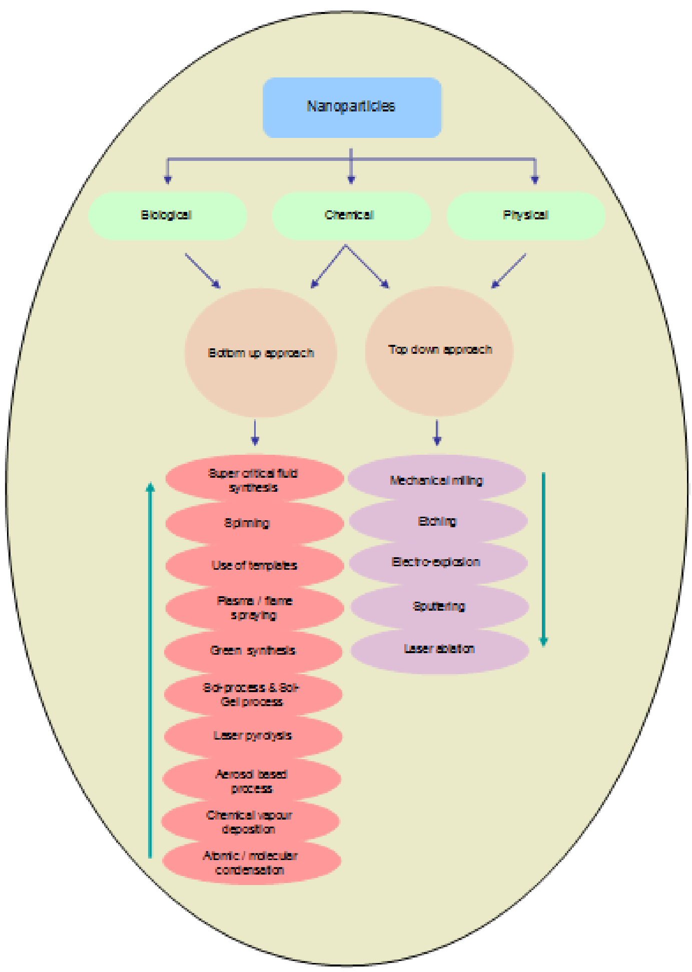

Figure 1: Process of preparation of nanoparticles

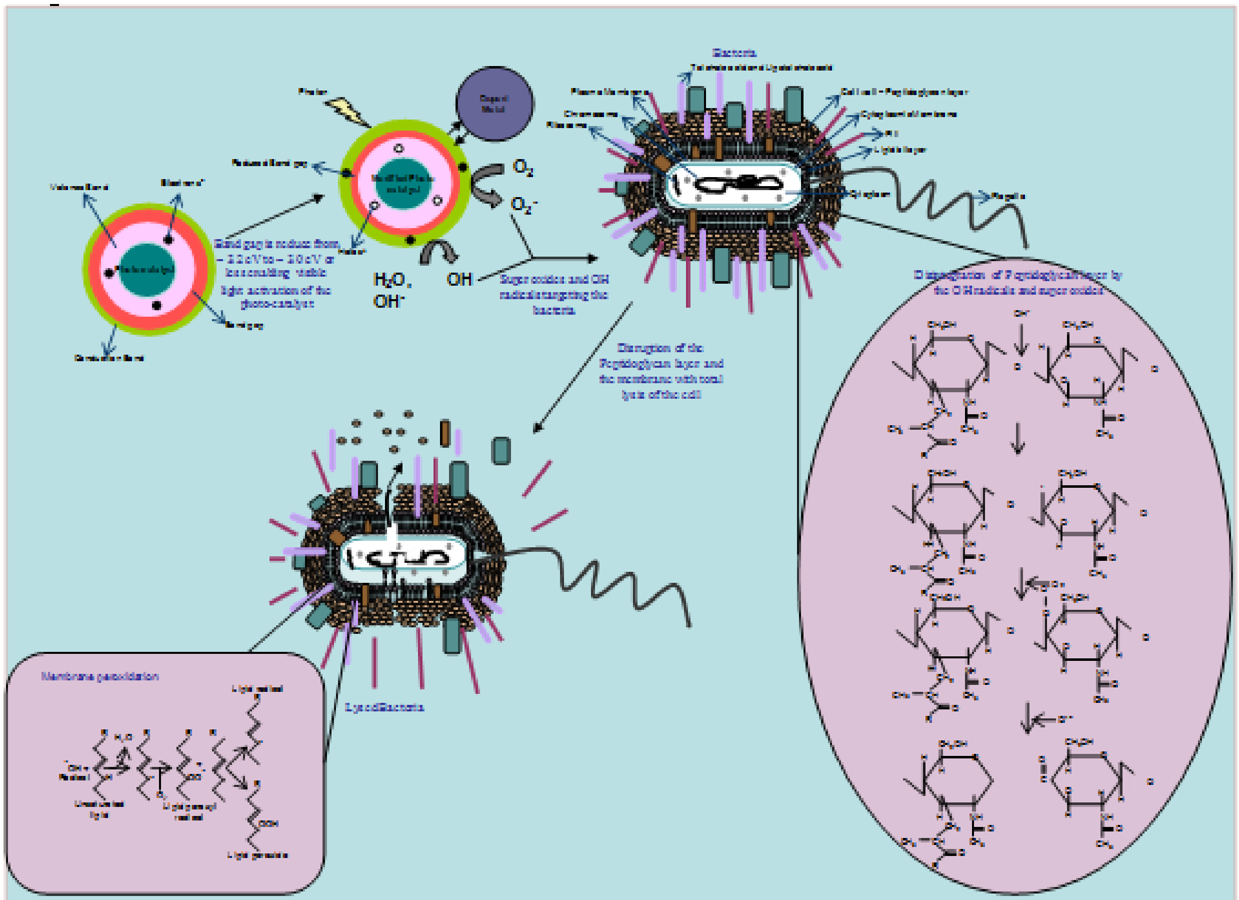

Figure 2: Mechanism of disinfection of chemical and biological nanoparticle

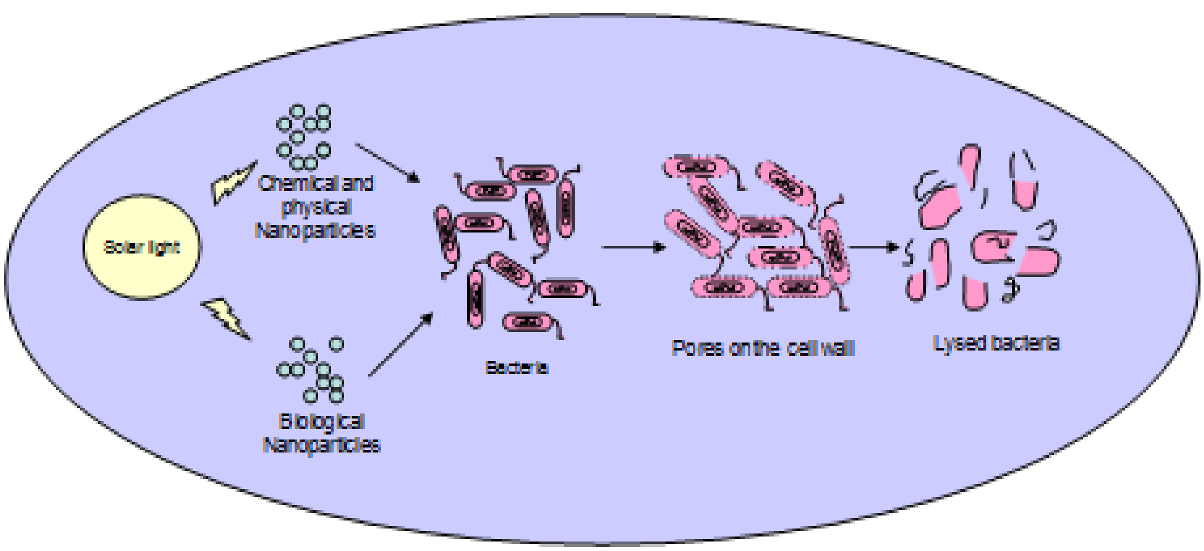

Figure 3: Schematic representation of bacterial cell wall and membrane disintegration, pit formation, membrane and lysis of bacteria by releasing the Cytoplasmic fluid

Table 1: Physical and chemical methods for the preparation of nanoparticles

Methods	**Description**
Sol-gel technique	It is a wet chemical technique used for the fabrication of metal oxides from a chemical solution which acts as a precursor for integrated network (gel) of discrete particles or polymers.
Solvothermal synthesis	It is a versatile low temperature route in which polar solvents are used under pressure and temperatures above their boiling points. Under solvothermal conditions, the solubility of reactants increases significantly, enabling reaction to take place at lower temperature.
Chemical reduction	It is the reduction of an ionic salt in an appropriate medium in the presence of surfactant using reducing agents.
Laser ablation	It is the process of removing material from a solid surface by irradiating with a laser beam. At low laser flux, the material is heated by absorbed laser energy and it evaporates or sublimates. At higher flux, the material is converted to plasma depending on the optical property and the laser wavelength.
Inert gas condensation	It is a process where different metals are evaporated in separate crucibles inside an ultra high vacuum chamber filled with helium or argon gas at typical pressure of few 100 pascals. As a result of inter atomic collisions the evaporated metal atoms condense in to small crystals and accumulates on liquid nitrogen filled cold finger.

Table 2: Reported chemical and biological nanoparticles for disinfection

Origin	**Metals**	**Size**	**Morphology**	**Effect**	**Reference**
Chemical Nanoparticles					
TiO_2, H_2O_2, TiO_2/H_2O_2	-	500 µm	-	Disinfection, *Enterococus* sp.	Lanao *et al.*, (2012)
TiO_2 suspension	-	25-200 nm	spherical	*E. coli*	Lydakis-Simantiris *et al.*, (2010)
Immobilized TiO_2	-	25-200 nm	spherical	*E. coli*	Alrousan *et al.*, (2009)
Palladium incorporated ZnO	Pl	15 nm	spherical	*E. coli*	Brayner *et al.*, (2006)
Ag on graphene oxide nonosheets	Ag	-	spherical	*S. aureus*, *E. coli*	Castellano *et al.*, (2007)
nAg	Ag	-	spherical	Bactericidal, disinfection	Matsumura *et al.*, (2003)
Fullerol	-	-	-	Bactericidal, disinfection	Bao *et al.*, (2011)
Carbon nanotubes	-	-	-	Bactericidal, disinfection	Holmes *et al.*, (1995)
nAg	Ag	-	spherical	*Pseudomonas aeruginosa*	Sondi and. Salopek-Sondi (2004)
ZnO	-	-	-	Bactericidal,	Huang *et al.*,

				disinfection	(2008)
Ag/ TiO_2	Ag	-	spherical	*E. coli* K12	Yamanaka *et al.*, (2005)
C- TiO_2		< 1µm	spherical	Degradation and disinfection	Hamal and Klabunde (2007)
Ag-water soluble polymer	Ag	-	-	*M. luteus, B. subtilis, B. cereus, E. coli, P. vulgaris, P. aeruginosa*	Chou *et al.*, (2005)
nWO_3	-	-	-	*E. coli*, Disinfection	Gondal *et al.*, (2009)
Plant Nanoparticles					
Aloe vera	Au, Ag	-	Spherical, triangular	Antimicrobial	Chandran *et al.*, (2006)
Carica papaya	Ag	10-50	Cubic and hexagonal	Disinfection of *E. coli, P. aeruginosa*	Vasanth Kumar *et al.*, (2010)
Citrullus colocynthis	Ag	-	Spherical	*E. coli, V. paraheamolyticus, P. Aeruginosa, Proteus vulgaris, L. monocytogens*	Satyavani *et al.*, (2011)
Azadirachta indica	Au/Ag		-	Disinfection	Huang *et al.*, (2000)
Murraya koenigii	Ag	40-80	-	*E. coli JM103, Staphyloccus aureus, P. aeruginosa*	Bonde *et al.*, (2012)
Dioscorea batatas	Ag	-	-	Disinfection, antimicrobial – *B. Subtilis, S. Aureus, E. Coli, S. Cerevisiae, C. albicans*	Nagajyothi and Lee (2011)
Basella alba, Helianthus annus, Oryza sativa, Saccharum officinarum, Sorghum bicolour, Zea mays	Ag	-	-	Atimicrobial activity	Leela and Vivekanandan (2008)
Vitex negundo	Ag	25-30	-	Antimicrobial – *E. coli, Staphylococcus aureus*	Zargar *et al.*, (2011)
Euphorbia nivulia latex	metallic	-	-	Disinfection of wastewater	Leela and Vivekanandan (2008)

Eucalyptus hybrida	Ag	-	-	Antimicrobial	Duran *et al.*, (2007)
Helianthus annus, Basella alba, Oryza sativa, Zea mays, Sorghum bicolo	Ag	-	-	Disinfection, Antimicrobial	Leela and Vivekanandan (2008)
Ocimum sanctum	Ag	4-30	-	*E. coli, S. aureus*	Song *et al.*, (2009)
Cacumen platycladi	Ag	-	-	*E. coli, S. aureus*	Shankar *et al.*, (2004)
Microorganism Nanoparticles					
Bacillus subtilis	Ag	-	-	Antimicrobial	Nair and Pradeep (2002)
Pseudomonas stutzeris	Ag	-	-	Antimicrobial	Husseiny *et al.*, (2007)
Aspergillus niger	Ag	-	-	*E. coli, S. aureus*	Gade *et al.*, (2008)
Sargassum wightii	Au	-	-	Antimicrobial	Kumar *et al.*, (2006)
Pseudomonas aeruginosa	Au	-	-	Antimicrobial	Husseiny *et al.*, (2007)
Shewanella oneidensis MR-1	Fe_2O_3	-	-	Antimicrobial	Suresh *et al.*, (2011)
Saccharomyces cerevisiae	Sb_2O_3	-	-	Antimicrobial	Duran *et al.*, (2007)
Fusarium oxysporum	ZrO_2	3–11	spherical	Antimicrobial	Bansal *et al.*, (2004)

Microbial Nanoparticles

Currently there is an urge for the development of environmentally benign nanoparticles and their synthesis protocols. Many nanoparticles have been developed employing microorganisms such as bacteria (Natarajan *et al.*, 2010), fungi (Duran *et al.*, 2005), Yeast (Zheng *et al.*, 2010) and algae (Singaravelu *et al.*, 2007) that has a demonstrable antimicrobial activity. Silver nanoparticles using *Klebsiella pneumoniae* was synthesized by Shahverdi *et al.*, (2007) and used for the disinfection of *Staphylococcus aureus* and *E. coli* at the same time. Pal *et al.*, (2007) have demonstrated that the efficacy of nanoparticles is shape dependent by studying the effect of various sizes and shapes of the nanoparticles in disinfection. On the other hand Duran *et al.*, (2007) synthesized silver nanoparticles using a fungi *Fusarium oxysporum* and studied its antibacterial properties.

Eukaryotic organisms such as fungi were thoroughly investigated for their ability to form nanoparticles with different element compositions and sizes (Gade *et al.*, 2008). Salem *et al.*, (2011) has reported the antibacterial activity of some marine red algae like *Cystoesira myrica*, *Cystoesira trinodis*, *Padina gymnospora*, *Sargassum dentifolium*, *Sargassum hystrix*, *Actinotrichia fragilis*, *Caulerpa raemosa* and *Codium fragile* over *Staphylococcus aureus* NCIMB 50080, *Bacillus cereus*, *E. coli* NCIMB 50034, *Enterococcus feacalis* NCIMB 50030, *Salmonella* sp. and *Pseudomonas aeruginosa*. *Spirulina platensis* a cyanobacteria, its extract was found to be capable of inhibiting the growth of *Staphylococcus aureus* and *Salmonella typhimurium* (Kumar *et al.*, 2006) (Table 2). Even though many researchers have reported the antimicrobial activity of many bacteria, fungi, yeast and algae; the lack of proper understanding in the preparation of nanoparticles using these microbicidal compounds for disinfection has created a lacuna in developing a technology for the synthesis and usage of nanoparticles.

Conclusion

The worldwide need for the clean water increased due to the increasing population, drought and the contamination of conventional water sources. Nanotechnology provides a good platform to modify and develop the important properties of metal in the form of nanoparticles having promising applications in diagnostics, biomarkers, cell labeling, contrast agents for biological imaging, antimicrobial agents, drug delivery systems and nano-drugs for treatment of various diseases (Singh and Singh, 2011). Water purification using nanotechnology either through filtration, adsorption or catalytic degradation was made possible by the development and the exploration of quantum world. Nanotechnology is being applied in the production of water purification membranes, nano wire membranes and filters (Yang and Li, 2008). Although, many nanoparticles have been developed with a demonstrable disinfection capacity, the challenge lies in the usage of an appropriate particle for the application of an efficient and economic filters or equipments for the process of disinfection. Nanotechnology can revolutionize the currently existing disinfection technology with its minimum cost and efficient removal of microbes. Ag and TiO_2 has long been known for its photocatalytic activity and disinfection capacity at the same time the awareness on the usage of most compatible, harmless and economic nanoparticle for the process of disinfection has always been a demanding area of research since past.

Many biological material (plant and microorganisms) based nanoparticles have been described for their microbicidal activity, but a development of proper technique for water disinfection is still under study. This paper has reviewed the current developments and techniques that have been discussed by various researchers worldwide in the field of disinfection, their limitations and advantages and the required developments in terms of research and technical needs for the development of an effective, economic and user friendly technique for disinfection.

ACKNOWLEDGEMENT

Authors are thankful to Director, NEERI, Nagpur, India, Director, CSIR-SERC, Chennai and the CSIR- for funding the project and allowing us to publish.

REFERENCES

Ahmad Z, Pandey R, Sharma S and Khuller GK (2005). Alginate nanoparticles as antituberculosis drug carriers: formulation development, pharmacokinetics and therapeutic potential. *Indian Journal of Chest Disease and Allied Science* **48** 171–176.

Alrousan DMA, Dunlop PSM, McMurray TA and Byrne JA (2009). Photocatalytic inactivation of *E. coli* in surface water using immobilised nanoparticle TiO_2 films. *Water Research* **43** 47–54.

Atmaca S, Gul K and Clcek R (1998). The effect of zinc on microbial growth. *Turkish Journal of Medical Science* **28** 595–97.

Bansal V, Rautaray D, Ahmad A and Sastry M (2004). Biosynthesis of zirconia nanoparticles using the fungus *Fusarium oxysporum*. *Journal of Materials Chemistry* **14** 3303–3305.

Bao Q, Zhang D and Qi P (2011). Synthesis and characterization of silver nanoparticle and graphene oxide nanosheet composites as a bactericidal agent for water disinfection. *Journal of Colloid and Interface Science* **360** 463-470.

Benabbou A K, Guillard C, Pigeot-Remy S, Cantau C, Pigot T and Lejeune P (2011). Water disinfection using photosensitizers supported on silica. *Journal of Photochemistry and Photobiology A: Chemistry* **219** 101–108.

Bodalo-Santoyo A, Gomez-Carrasco JL, Gomez-Gomez E, Maxumo-Martin F and Hidalgo-Montesinos AM (2003). Application of reverse osmosis to reduce pollutants present in industrial wastewater. *Desalination* **155** 101–108.

Bonde SR, Rathod DP, Ingle AP, Ade RB, Gade AK and Rai MK (2012). *Murraya koenigii* – mediated synthesis of silver nanoparticles and its activity against three human pathogenic bacteria. *Nanoscience Methods* **1** 25-36.

Brayner R, Ferrari-Iliou R, Brivois N, Djediat S, Benedetti MF and Fievet F (2006). Toxicological impact studies based on *Escherichia coli* bacteria in ultrafine ZnO nanoparticles colloidal medium. *Nano Letters* **6** 866–6870.

Brunner TI, Wick P, Manser P, Spohn P, Grass RN, Limbach LK, Bruinink A and Stark WJ (2006). In vitro cytotoxicity of oxide nanoparticles: comparison to asbestos, silica, and effect of particle solubility. *Environmental Science Technology* **40** 4374-4381.

Castellano JJ, Shafii SM, Ko F, Donate G, Wright TE and Mannari RJ (2007). Comparative evaluation of silver-containing antimicrobial dressings and drugs. *International Wound Journal* **4** 114–122.

Chandran SP, Chaudhary M, Pasricha R, Ahmad A and Sastry M (2006). Synthesis of gold nanotriangles and silver nanotriangles using *Aloe vera* plant extract. *Biotechnology Progress* **22** 577–579.

Chen XC and Schluesenera HJ (2008). Nanosilver: a nanoproduct in medical application. *Toxicology Letters* **176** 1–12.

Chong MN, Jin B, Chow CWK and Saint C (2010). Recent developments in photocatalytic water treatment technology: A review. *Water Research* **44** 2997-3027.

Chou WL, Yu DG and Yang MC (2005). The preparation and characterization of silver-loading cellulose acetate hollow fiber membrane for water treatment. *Polymers for Advanced Technologies* **16** 600–607.

Du L, Jiang H, Liu X, Wang E. (2007). Biosynthesis of gold nanoparticles assisted by *Escherichia coli DH5α* and its application on direct electrochemistry of hemoglobin. *Electrochemistry Communications* **9** 1165–1170.

Dubey M, Bhadauria S and Kushwah BS (2009). Green synthesis of nanosilver particles from extract of *Eucalyptus Hybrida* (Safeda) leaf. *Digest Journal of Nanomaterials and Biostructures* **4** 537–543.

Duran N, Marcato PD, De S, Gabriel IH, Alves OL and Esposito E (2007). Antibacterial effect of silver nanoparticles produced by fungal process on textile fabrics and their effluent treatment. *Journal of Biomedical Nanotechnology* **3** 203- 208.

Duran N, Marcato PD, Alves OL and Souza G (2005). Mechanistic aspects of biosynthesis of silver nanoparticles by several *Fusarium oxysporum* strains. *Journal of Nanotechnology* **3** 8-12.

Feng QL, Wu J, Chen GQ, Cui FZ, Kim TN and Kim JO (2000). A mechanistic study of the antibacterial effect of silver ions on *Escherichia coli* and *Staphylococcus aureus*. *Journal of Biomedical Materials Research* **52** 662–668.

Franklin NM, Rogers NJ, Apte SC, Batley GE, Gadd GE and Casey PS (2010). Comparative toxicity of nanoparticulate ZnO, bulk ZnO, and ZnC_{l2} to a freshwater microalga (*Pseudokirchneriella subcapitata*): the importance of particle solubility. *Environmental Science and Technology* **41** 8484–8490.

Fu XZ, Zeltner WA and Anderson MA (1995). The gas-phase photocatalytic mineralization of benzene on porous titania-based catalysts. *Applied Catalysis B: Environmental Journal* **6** 209–224.

Gade AK, Bonde P, Ingle AP, Marcato PD, Duran N and Rai MK (2008). Exploitation of *Aspergillus niger* for synthesis of silver nanoparticles. *Journal of Biobased Materials and Bioenergy* **2** 243–247.

Gardea-Torresdey JL, Gomez E, Peralta-Videa JR, Parsons JG, Troiani H and Jose-Yacaman M (2003). Alfalfa sprouts: a natural source for the synthesis of silver nanoparticles. *Langmuir* **19** 1357-1361.

Gogoi SK, Gopinath P, Paul A, Ramesh A, Ghosh SS and Chattopadhyay A (2006). Green fluorescent protein expressing *Escherichia coli* as a model system for investigating the antimicrobial activities of silver nanoparticles. *Langmuir* **22** 9322–9328.

Gondal MA, Dastageer MA and Khalil A (2009). Synthesis of nano-WO_3 and its catalytic activity for enhanced antimicrobial process for water purification using laser induced photo-catalysis. *Catalysis Communications* **11** 214-219.

Gong P, Li H, He X, Wang K, Hu J and Tan W (2007). Preparation and antibacterial activity of Fe_3O_4@Ag nanoparticles. *Nanotechnology* **18** 604–611.

Gu H, Ho PL, Tong E, Wang L and Xu B (2003). Presenting vancomycin on nanoparticles to enhance antimicrobial activities. *Nanotechnology Letters* **3** 1261–1263.

Hamal DB and Klabunde KJ (2007). Synthesis, characterization and visible light activity of new nanoparticle photocatalysts based on silver, carbon and sulphur-doped TiO_2. *Journal of Colloid and Interface Science* **311** 514-522.

Holmes NC, Ross M and Nellis NJ (1995). Temperature measurements and dissociation of shock-compressed liquid deuterium and hydrogen. *Physical Review B* **52** 15835-15845.

Huang Z, Zheng X, Yan D, Yin G, Liao X, Kang Y, Yao Y, Huang D and Hao B (2008). Toxicological effect of ZnO nanoparticles based on bacteria. *Langmuir* **24** 4140–4144.

Huang J, Li Q, Sun D, Lu Y, Su Y and Yang X (2007). Biosynthesis of silver and gold nanoparticles by novel sundried *Cinnamomum camphora* leaf. *Nanotechnology* **18** 105104-105115.

Huang Z, Maness PC, Blake DM, Wolfrum EJ, Smolinksi SL and Jacoby WA (2000). Bactericidal mode of titanium dioxide photocatalysis. *Journal of Photochemistry and Photobiology A* **130** 163–170.

Husseiny MI, El-Aziz MA, Badr Y and Mahmoud MA (2007). Biosynthesis of gold nanoparticles using *Pseudomonas aeruginosa*. *Spectrochimica Acta Part A* **67** 1003–1006.

Jain D, Kumar Daima H, Kachhwaha S and Kothari SL (2009). Synthesis of plant-mediated silver nanoparticles using papaya fruit extract and evaluation of their antimicrobial activities. *Digest Journal of Nanomaterials and Biostructures* **4** 557-563.

Jha AK and Prasad K (2009). A green low-cost biosynthesis of Sb_2O_3 nanoparticles. *Biochemical Engineering Journal* **43** 303–6.

Kawahara K, Tsuruda K, Morishita M and Uchida M (2000). Antibacterial effect of silver zeolite on oral bacteria under anaerobic condition. *Dental Materials* **16** 452–5.

Klaus-Joerger T, Joerger R, Olsson E and Granqvist CG (2001). Bacteria as workers in the living factory: metal-accumulating bacteria and their potential for materials science. *Trends in Biotechnology* **19** 15–20.

Korbekandi H, Iravani S and Abbasi S (2009). Production of nanoparticles using organisms. *Critical Reviews in Biotechnology* **29** 279-306.

Kumar P, Angadi S and Vidyasagar G (2006). Antimicrobial activity of blue Green and green algae. *Indian Journal of Pharmaceutical Science* **68** 647-648.

Lanao M, Ormad MP, Mosteo R and Ovelleiro JL (2012). Inactivation of *Enterococcus* sp. by photolysis and TiO_2 photocatalysis with H_2O_2 in natural water. *Solar Energy* **86** 619-625.

Leela A and Vivekanandan M (2008). Tapping the unexploited plant resources for the synthesis of silver nanoparticles. *African Journal of Biotechnology* **7** 3162–3165.

Leung TY, Chan CY, Hu C, Yu JC and Wong PK (2008). Photocatalytic disinfection of marine bacteria using fluorescent light. *Water Research* **42** 4827-4837.

Li D, Haneda H, Labhsetwar NK, Hishita S and Ohashi N (2005). Visible-Light-Driven Photocatalysis on Fluorine-Doped TiO2 Powders by the Creation of Surface Oxygen Vacancies. *Chemical Physics Letters* **401** 579–584.

Lu ZX, Zhou L, Zhang ZL, Shi WL, Xie ZX, Xie HY, Pang DW and Shen P (2003). Cell damage induced by photocatalysis of TiO_2 thin films. *Langmuir* **19** 8765 –8768.

Lydakis-Simantiris N, Riga D, Katsivela E, Mantzavinos D and Xekoukoulotakis NP (2010). Disinfection of spring water and secondary treated municipal wastewater by TiO_2 photocatalysis. *Desalination* **250** 351–355.

Malato S, Caceres J, Aguera A, Mezcua M, Hernando D, Vial J and Fernandez-Alba AR (2001). Degradation of imidacloprid in water by photo-Fenton and TiO_2 photocatalysis at a solar pilot plant: a comparative study. *Environmental Science and Technology* **35** 4359–4366.

Marugan J, Van Grieken R, Pablos C and Sordo C (2010). Analogies and differences between photocatalytic oxidation of chemicals and photocatalytic inactivation of microorganisms. *Water Research* **44** 789–96.

Review Article

Mathabe MC, Nikolova RV, Lall N and Nyazema NZ (2006). Antibacterial activities of medicinal plants used for the treatment of diarrhoea in Limpopo province. *South African Journal of Ethnopharmacology* **105** 286-293.

Matsumura Y, Yoshikata K, Kunisaki S and Tsuchido T (2003). Mode of bactericidal action of silver zeolite and its comparison with that of silver nitrate. *Applied and Environmental Microbiology* **69** 4278–4281.

Matsunaga T, Tomada R, Nakajima T and Wake H (1985). Photochemical sterilization of microbial cells by semiconductor powders. *FEMS Microbiology Letters* **29** 211–214.

Morones JR, Elechiguerra JL, Camacho A, Holt K, Kouri JB, Ramirez JT and Yacaman MJ (2005). The bactericidal effect of silver nanoparticles. *Nanotechnology* **16** 2346–2353.

Murthy YLN, Rao TK, Viswanath IVK and Singh R (2010). Synthesis and characterization of nano silver ferrite composite. *Journal of Magnetism and Magnetic Materials* **322** 2071–2074.

Nagajyothi P and Lee KD (2011). Synthesis of plant – mediated silver nanoparticles using *Dioscorea balatas* rhizome extract and evaluation of their antimicrobial activities. *Journal of Nanomaterials* 1-7.

Nair B and Pradeep T (2002). Coalescence of nanoclusters and formation of submicron crystallites assisted by *Lactobacillus* strains. *Crystal Growth & Design* **2** 293-298.

Natarajan K, Subbalaxmi SV and Ramchandra M (2010). Microbial production of silver nanoparticles. *Digest Journal of Nanomaterials and Biostructures* **5** 135 –40.

Pal S, Tak YK and Song JM (2007). Does the antibacterial activity of silver nanoparticles depend on the shape of the nanoparticle? A study of the gram-negative bacterium *Escherichia coli*. *Applied and Environmental Microbiology* **73** 1712–1720.

Parvulescu VI, Cojocaru B, Parvulescu V, Richards R, Li Z, Cadigan C, Granger P, Miquel P and Hardacre C (2010). Sol-gel-entrapped nano silver catalysts-correlation between active silver species and catalytic behavior. *Journal of Catalysis* **272** 92–100.

Pera-Titus M, Garcı´a-Molina V, Banos MA, Gime´nez J and Esplugas S (2004). Degradation of chlorophenols by means of advanced oxidation processes: a general review. *Applied Catalysis B: Environmental* **47** 219-56.

Qu J, Yuan X, Wang X and Shao P (2011). Zinc accumulation and synthesis of ZnO nanoparticles using *Physalis alkekengi* L. *Environmental Pollution* **159** 1783-1788.

Rajesh W, Raut NS, Kolekar JR, Lakkakula VD, Mendhulkar SB and Kashid R (2010). Extracellular synthesis of silver nanoparticles using dried leaves of *Pongamia pinnata* (L) Pierre. *Micro & Nano Letters* **2** 106–113

Raveendran P, Fu J and Wallen SL (2003). Completely “Green” Synthesis and Stabilization of metal nanoparticles. *Journal of American Chemical Society* **125** 13940-13941.

Retchkiman-Schabes PS, Canizal G, Becerra-Herrera R, Zorrilla C, Liu HB and Ascencio JA (2006). Biosynthesis and characterization of Ti/Ni bimetallic nanoparticles. *Optical Materials* **29** 95–99.

Ryu H, Gerrity D, Crittenden JC and Abbaszadegan M (2008). Photocatalytic inactivation of *Cryptosporidium parvum* with TiO_2 and low-pressure ultraviolet irradiation. *Water Research* **42** 1523–1530.

Salem WM, Galal H and Nasr El-deen F (2011). Screening for antibacterial activities in some marine algae from the red sea (Hurghada, Egypt). *African Journal of Microbiology Research* **5**(15) 2160-2167.

Santhoshkumar T, Rahuman AA, Rajakumar G, Marimuthu S, Bagavan A, Jayaseelan C, Zahir AA, Elango G and Kamaraj C (2011). Synthesis of silver nanoparticles using *Nelumbo nucifera* leaf extract and its larvicidal activity against malaria and filariasis vectors. *Parasitology Research* **108** 693–702.

Satyavani K, Ramanathan T and Gurudeeban S (2011). Plant mediated synthesis of biomedical silver nanoparticles by using leaf extract of *Citrullus colocynthis*. *Research Journal of Nanoscience and Nanotechnology* **1** 95-101.

Shahverdi AR, Fakhimi A, Shahverdi HR and Minanian S (2007). Synthesis and effect of silver nanoparticles on the antibacterial activity of different antibiotics against *S. aureus* and *E. coli*. *Nanomedicine* **3** 168–171.

Shankar SS, Ahmad A, Rai A and Sastry M (2004). Rapid synthesis of Au, Ag and bimetallic Au core-Ag shell nanoparticles by using neem (*Azadirachta indica*) leaf broth. *Journal of Colloid and Interface Science* **275** 496–502.

Sharma VK, Yngard RA and Lin Y (2009). Silver nanoparticles: Green synthesis and their antimicrobial activities. *Advances in Colloid and Interface Science* **145** 83–96.

Singaravelu G, Arockiamary JS, Kumar VG and Govindaraju K (2007). A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, *Sargassum wightii* Greville. *Colloids and Surfaces B* **57** 97–101.

Singh R and Singh NH (2011). Medical applications of nanoparticles in biological imaging, cell labeling, antimicrobial agents, and anticancer nanodrugs. *Journal of Biomedical Nanotechnology* **7** 489–503.

Singh M, Manikandan S and Kumaraguru AK (2011). Nanoparticles: A new technology with wide applications. *Research Journal of Nanoscience and Nanotechnology* **1** 1-11.

Sondi I and Salopek-Sondi B (2004). Silver nanoparticles as antimicrobial agent: a case study on *E. coli* as a model for gram-negative bacteria. *Journal of Colloid and Interface Science* **275** 177–182.

Song JY, Jang HK and Kim BS (2009). Biological synthesis of gold nanoparticles using *Magnolia kobus* and *Diopyros kaki* leaf extracts. *Process of Biochemistry* **44** 1133-1138.

Sontakke S, Modak J and Madras G (2010). Photocatalytic inactivation of *Escherischia coli* and *Pichia pastoris* with combustion synthesized titanium dioxide. *Chemical Engineering Journal* **165** 225–233.

Spacciapoli P, Buxton D, Rothstein D and Friden P (2001). Antimicrobial activity of silver nitrate against periodontal pathogens. *Journal of Periodontal Research* **36**(2) 108–113.

Sun C, Li Q, Gao S, Cao L and Shang JK (2010). Enhanced photocatalytic disinfection of E. coli bacteria by silver modification of nitrogen-doped titanium dioxide nanoparticle photocatalyst under visible-light illumination. *Journal of the American Ceramic Society* **93** 3880-3885.

Suresh AK, Pelletier DA and Wang W (2011). Biofabrication of discrete spherical gold nanoparticles using the metal reducing bacterium *Shewanella oneidensis*. *Acta Biomaterialia* **7** 2148–2152.

Vasanth Kumar R and Ghulam Raza T (2009). Photocatalytic disinfection of water with Ag-TiO2 nanocrystalline composite. *Ionics* **15** 579-587.

Vasanth Kumar K, Monteiro de Castro M, Martinez-Escandell M, Molina-Sabio M and Rodriguez-Reinoso F (2010). A Continuous Binding Site Affinity Distribution Function from the Freundlich Isotherm for the Supercritical Adsorption of Hydrogen on Activated Carbon. *Journal of Physical Chemistry C* **114** 13759–13765.

World Health Organization (2008). Guidelines for Drinking-Water Quality, Incorporating 1st and 2nd addenda **1**(3).

Wu P, Xie R, Imlay JA and Shang JK (2009). Visible-light-induced photocatalytic inactivation of bacteria by composite photocatalysts of palladium oxide and nitrogen-doped titanium oxide. *Applied Catalysis B: Environmental* **88** 576–581.

Xu XH, Brownlow WJ, Kyriacou SV, Wan Q and Viola JJ (2004). Real-time probing of membrane transport in living microbial cells using single nanoparticle optics and living cell imaging. *Biochemistry* **43** 10400–10413.

Yamanaka M, Hara K and Kudo J (2005). Bactericidal Actions of a Silver Ion Solution on Escherichia coli, Studied by Energy-Filtering Transmission Electron Microscopy and Proteomic Analysis. *Applied and Environmental Microbiology* **71**(11) 7589–7593.

Yang GCC and Li CJ (2008). Tubular TiO_2/Al_2O_3 composite membranes: preparation, characterization and performance in electrofiltration of oxide-CMP wastewater. *Desalination* **234** 354-61.

Review Article

Yang K (2001). Prokaryotic Calmodulins: Recent developments and evolutions. *Journal of Molecular Microbiology and Biotechnology* **3** 457-459.

Zargar M, Hamid AA, Bakar FA, Shamsudin MN, Shameli K, Jahanshiri F and Farahani F (2011). Green synthesis and antibacterial effect of silver nanoparticles using *Vitex negundo* L. *Molecules* **16** 6667-6676.

Zhang X, Gu H and Fujii M (2007). Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. *Experimental Thermal and Fluid Science* **31** 593–99.

Zhao W, Ma W, Chen C, Zhao J and Shuai Z (2004). Efficient Degradation of Toxic Organic Pollutants with Ni_2O_3/TiO_2-xBx under Visible Irradiation. *Journal of the American Chemical Society* **126** 4782–3.

Zheng D, Hu C, Gan T, Dang X and Hu S (2010). Preparation and application of a novel vanillin sensor based on biosynthesis of Au-Ag alloy nanoparticles. *Sensors and Actuators B: Chemical* **148** 247–52.

Zhu J, Chen F, Zhang J, Chen H and Anpo M (2006). Fe_3^+-TiO_2 photocatalysts prepared by combining sol-gel method with hydrothermal treatment and their characterization. *Journal of Photochemistry and Photobiology A* **180** 196-204.