Review Article

Bacterial Cell – A Bioreactor for the Synthesis of Nanoparticles

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Abstract

Nanotechnology is an interdisciplinary science which is rapidly progressing in the recent past. Nanoparticles (NPs) exhibit unique properties that label them as molecules having potential applications in engineering, medical and environmental research fields. Due to the limitations associated with the conventional methods of nanoparticle synthesis, there is an upsurge in biological means of nanoparticle synthesis. Nature has bestowed with diverse defence mechanisms in bacteria that help them to survive in any extreme environmental conditions. This property has been righteously exploited by the scientists to meet their need with respect to nanoparticle synthesis. Although extensive reports are available on bacteriogenic synthesis of NPs, the underlying mechanism is yet to be explored. Since bacteria can be easily handled and genetically altered, it can serve as a best system to fabricate nanoparticles with desired physiological properties.

Key words : Nanoparticles, Bionanosynthesis, Bacteriogenic Nanosynthesis, Bioreduction

Introduction

Particulate substances whose size is measurable in the range of 1-100nm (sometimes less than 500nm) are referred as nanoparticles (NPs) and it can be made using wide variety of materials. NPs take up different shapes such as spherical, tubular and irregular shapes and exist as single, fused or aggregated.[1] With respect to dimension, NPs can be zero dimension (0D-quantum dots), one dimension (1D - nanowires), 2 dimension (2D – nanometer thick films) and 3 dimension (3D-nano- particles).[2] Most of the NPs are shown to be composed of three layers; i) surface layer – the outermost layer which can be functionalised by small molecules, metal ions or polymers ii) shell layer – the middle layer whose chemical properties show much difference compared to the inner core and iii) core – the central part that represents the NPs itself.[3] Based on their physical and chemical properties, the NPs have been grouped into different categories such as Carbon based NPs, Metal NPs, Ceramics NPs, Semiconductor NPs, Polymeric NPs, Lipid based NPs. Discovery of the fact that the size of the substances influence their physical and chemical properties revolutionized the field of nanotechnology. Reduction in size actually imparts some unique properties to the materials more notably, the large surface area, quantum confinement, optical and magnetic properties etc.[4]

Enormous development in the technical aspect has allowed the scientists to tailor up the materials to meet their need. Flooded research on the improvement of nanoparticles have made them almost indispensable in all areas such as engineering, electronics, environmental remediation and health care etc. Integration of biomolecules with nanoparticles have made great impact on drug and gene delivery, bio-sensing and bio-imaging thus, nanotechnology has been deep-rooted in the field of biology and medicine that actually gave rise to a new field of study called Nanobiotechnology.[5] Owing to its plethora of applications, scientists across the globe are exploiting various sources for the synthesis of NPs. There are many techniques available for the synthesis of NPs, some of them are ultraviolet irradiation, aerosol technologies, lithography, laser ablation, ultrasonic fields and photochemical reduction techniques.[6-10] The involvement of hazardous chemicals, complex procedure and expensiveness have become a subject of paramount concern.[11,12] Recent development in exploiting microbes and plants for the synthesis of NPs have become a major breakthrough since this approach is found to be safe, eco-friendly, cost effective and sustainable.[13-15] This review details how microbes especially bacteria are being exploited for the synthesis of NPs.

Microbes the green Nanofactories

Usage of microorganisms such as bacteria, fungi and yeast for the synthesis of NPs are gaining momentum in recent years as they possess certain advantages over the conventional methodologies. Various enzyme systems, co factors and metal resistant genes of the microbial system help in the detoxification of heavy metals, reduction of metal salt into metal nanoparticles and further they provide natural capping thereby prevent nanoparticle aggregation leading to increase in stability.[16, 17] Microbes have the capacity to reduce metal ions either intra or extracellularly, however the precise mechanism involved in the synthesis of NPs is yet to be uncovered. Different biological agents react differently with the metal ions that pose difficulty for the scientists to understand the exact process. Nevertheless, intracellular and extracellular means of NPs synthesis remains the two major approaches. Array of protocols have been reported till date that employs microbial biomass, supernatant and derived components.[18, 19]

Intracellular synthesis

Intracellular synthesis of NPs in certain bacteria has helped the researchers to understand the mechanism to some extent. The process takes place in step wise manner that involves trapping, bio-reduction and capping. The ion transport proteins present on the cell wall of the bacteria play a major role in transporting the metal ions; this is further facilitated by the electrostatic interaction between the negatively charged cell wall and positively charged metal ions. Metal ions form cluster in the case of Lactobacillus species which strengthens the electrostatic interaction between the cell surface and metal ions. The enzymes present within the cell wall reduce the metal ions into metal NPs. Thus formed NPs or the cluster of NPs get into the cell by diffusion through the cell wall (Fig 1).[20] The basic experimental steps involved in the synthesis of NPs are as follows; the bacterial cells are grown to an optimal stage, centrifuged and the cells pellet is washed. The filter sterilized metal salt solution is co-incubated with the cell suspension. Formation of NPs can be monitored by visualizing the colour change in the medium. The cells are washed and lysed by ultra-sonication which releases the NPs that can be centrifuged, purified and collected.[19, 21] Down-stream processing is a cumbersome procedure in case of intracellular synthesis of NPs and that seems to be a primary limitation of this approach.

Extracellular synthesis

The enzyme nitrate reductase which was secreted extracellularly by the fungi had the capability to reduce the $AgNO_3$ into AgNPs, this finding actually helped in the understanding of mechanism of extra-cellular synthesis of NPs. Subsequently, number of studies were reported supporting this observation.[22-23] A similar mechanism involving the co factor NADH and NADH dependent enzyme in the conversion of Au ions into AuNPs has been reported in *Rhodopseudomonas capsulate*.[24] Recent studies have reported the importance of cytochromes and redox mediators in the promotion of extracellular synthesis of NPs. Exopolysaccharides (EPS) secreted extracellularly in most of the bacteria has been shown to play a major role in the synthesis of NPs. Detailed investigation has revealed that the aldehyde and hemiacetal groups present in the EPS act as reducing agent. It is generally accepted that when the metal ions bind to the EPS containing the active moieties, get chelated, reduced and stabilised. Moreover, the polyanionic groups such as hydroxyl, carboxyl, phosphoric, hemiacetal and amino end groups play important role in reducing the metal

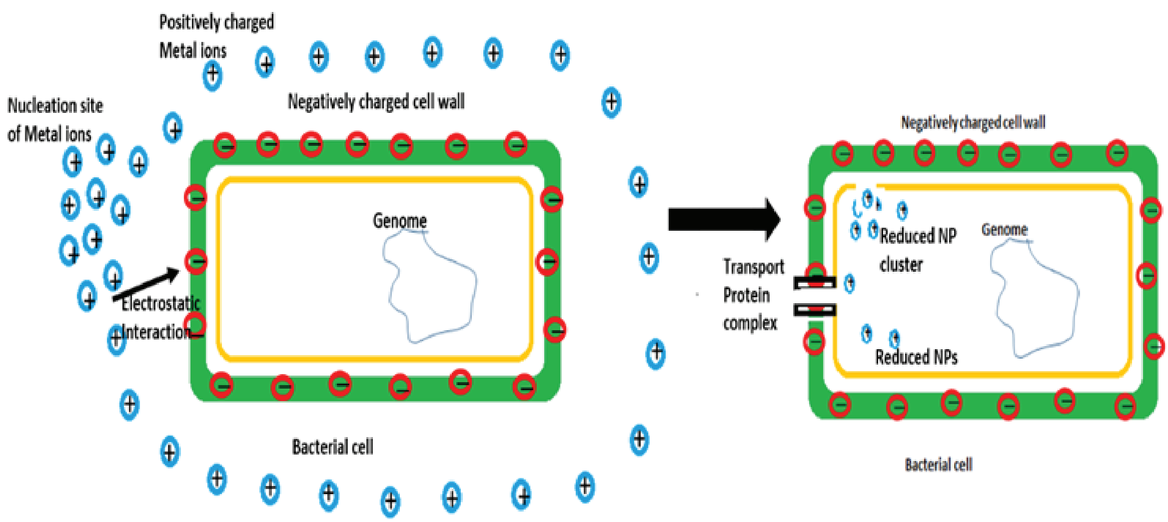

Figure 1: Schematic illustration showing the mechanism involved in the intracellular mediated nanoparticle synthesis in bacteria

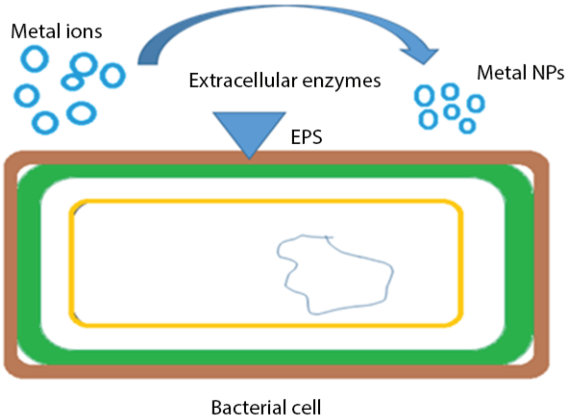

Figure 2: Schematic illustration showing the extracellular synthesis of nanoparticles by bacteria.

ions as well as in enhancing the electrostatic interaction between the metal ions and EPS (Figure 2).[25] For extracellular synthesis of NPs, the bacteria is initially grown to optimal level and then centrifuged to separate the biomass. The supernatant is collected to which the filter sterilized metal salt solution is added and monitored for colour change. Change in colour indicates the formation of NPs for example, the change in color from pale yellow to brownish color indicates the formation of silver NPs, pale yellow to pinkish color indicates the formation of gold NPs, and the formation of whitish yellow to yellow color indicates the formation of manganese and zinc NPs.[19, 21]

Bacterial synthesis of NPs

Bacteria are the tiniest life on the earth that dwells in diverse environmental conditions from terrestrial to deep sea. Bacteria can get adapted to any changing conditions by acquiring favourable mutations in them. In this way bacterium presents a wide variety of biological processes, novel regulatory functions, enzyme systems and other molecules/compounds which serve as a best platform to carry out various research activities. Synthesis of metal NPs by the bacterial cells is a kind of natural defence mechanism that the cell employ to detoxify the higher concentration of metal ions. The commonly used bacterial species for the synthesis of NPs are *Escherichia coli, Bacillus cereus, Lactobacillus species, Klebsiella pneumoniae, Corynebacterium species, Pseudomonas species,* Ochrobactrum and Acinetobacter species.[26-27] Bacterial synthesis of NPs dates back to 1980s when Beveredge and Murray[28] first time reported the synthesis of Au NP by *Bacillus subtilis,* however, the resurgence was appeared only after 2000 followed by the report of Ag NPs (200nm) synthesis by *Pseudomonas stutzeri* AG259.[29] In 2008, extracellular synthesis of Ag NPs (50nm) was demonstrated using the supernatant of *B. licheniformis.*[30] It was reported that *Pseudomonas aeruginosa* could intracellularly synthesize variety of metal NPs such as Pd, Ag, Rh, Ni, Fe, Co, Pt, and Li. A novel marine strain, *Kocuria flavahas* been reported to synthesize copper nanoparticle with particle size within the range of 5 to 30 nm.[31] *Lactobacillus plantrum* and *Aeromonas hydrophila* are shown to be involved in biosynthesis of ZnO NPs.[32,33] Synthesis of triangular shaped CuO NPs by *Halomona selongate* has been reported recently.[34]

Recent report on biosynthesis of magnetite NPs by different microorganisms namely, *Magnetotactic bacterium* MV-1, MS-I, *M. gryphiswaldense, Candidatus magnetoglobus* multicellular adds more value to this aspect of research. Further the simple *Bacillus cereus* has been shown to synthesize super paramagnetic iron oxide nanoparticles (29 nm). Perez-Gonzalez et al have revealed the mechanisms used for the fabrication of magnetite NPs by *Shewanella oneidensis*. As per their report, when ferrihydrite is provided/available, bacteria utilize it as a final electron acceptor that elevates the pH around the cell resulting in active production of Fe2+ ions. This further leads to the accumulation of Fe2+ and Fe3+ at cell wall causing super-saturation state of the cell. Synthesis of bacterial magnetite particle (BacMP) starts with the formation of small vesicles. Then vesicles are joined in chains along with cytoskeletal filaments. The assemblage of Fe2+ inside the vesicles by iron transporters is the next step of BacMP synthesis. Finally, proteins attached to BacMP initiate nucleation and also regulate the morphology of magnetite crystals. Several proteins attached to the BacMP membrane plays an important role for the generation of magnetite.[35, 36] While biosynthesis of highly monodispersed NPs is still a challenging one, the marine cyanobacterium *Phormidium fragile* has been reported to synthesise highly monodispersed Ag NPs with the size in the range of 5–6.5 nm. Furthermore, biosynthesis of bimetallic Ag-Au nanostructures has also been demonstrated using bacterial strains. *E. coli* DH5α has been shown to produce morphologically different for example round, triangular or hexagonal AuNPs.[37] Cadmium sulphide (CdS), the semiconductor nano crystals were shown to get accumulated intracellularly in *Klebsiella pneumonia, E. coli* and *Clostridium thermoaceticum.*[38,39] Bio-reduction of selenite to selenium (a non-metallic NP) has been observed in various bacterial species namely, *Stenotrophomona smaltophilia* SELTE02, *Enterobacter cloacea* SLD1a-1, *Rhodo spirullumrubrum, Tetrathiobacter kashmirensis, P. stutzeri, Desulfovibrio desulfuricans, E. coli*. These microbes were able to synthesize Se NPs in different shapes like granular, circular, fibrillar and they were found to be deposited either in cell cytoplasm or periplasmic space, some cases it was synthesised extracellularly.[40,41] The very common Lactobacillus strains have also shown to synthesize Titanium NPs.[42] Sharma et al,[43] reported that a novel marine bacterial strain, *Marinobacter Pelagius* was able to produce stable, monodisperse gold nanoparticles.

Advances and Challenges in Bionanosynthesis

A study report suggest that reduction of aqueous Ag+ ion using the culture supernatants of *Klebsiella pneumoniae, Escherichia coli,* and *Enterobacter cloacae* hasten the process of fabrication of AgNPs.[19, 44,45] Researchers have successfully made the common bacterial strain present in the buttermilk namely, Lactobacillus, to synthesizes both Au and Ag NPs under standard conditions.[20] Varshney et al[46] have reported a rapid biological synthesis technique for the synthesis of spherical Cu NPs in the size range of 8–15 nm using non-pathogenic *Pseudomonas stutzeri*. It has been shown that the morphological pattern of NPs can be controlled by using microorganisms. Furthermore, the pH of the environment has been shown to influence the size of the NP formed. The bacteria *R. capsulata* synthesized gold NPs of size range between 10 and 20 nm at pH 7, while gold nano plates were formed at pH 4.[47] It is reported that bacteria could synthesize NPs as hollow metal microspheres/ tubes, such hollow assemblies possess superior photo-catalytic activity compared with the corresponding solid counterparts.[17] When the NPs are synthesised biologically, the capping and stabilizing agents are not added externally since the biomolecules take care of these functions.[48] These biomolecules also functionalize the nanoparticles, making it more effective relative to NPs synthesized through non-biological means.[5]

The process of microbes mediated synthesis of NPs is rather slow compared to the conventional (physical/chemical) methods. The rate of synthesis of NPs depends upon the rate of growth and metabolism of the microorganisms. The growth and metabolic rate of any microbe get easily affected by the surrounding environmental factors in particular pH, temperature, nutrition availability, osmotic conditions etc.[49] Although some studies have shown the mechanism involved in bacteriogenic NP synthesis, further exploration in this aspect is very much necessary for tailoring the NP synthesis depending upon the need. Detailed investigation on catalytic proteins, reducing enzymes and stabilizing molecules would certainly provide sufficient information to manipulate the physiological properties of the NPs. Downstream processing is the one another step where scientists struggle. Exploring the microbial diversity to search for novel and sustainable microorganisms to biosynthesize NPs. Extensive research focused on the aforesaid points will improve the microbe especially bacteria mediated NP synthesis.

Applications

Nanoparticles display unique biological, physical and chemical properties having potential application in plethora of scientific areas such as environmental, biomedical, agricultural etc. In recent past, there has been a progressive research on NPs with respect to biomedical applications. Significant number of studies report that most of the metal NPs (Ag Nps, ZnO NPs) exhibit anti-microbial activity.[50,51] Ag NPs are also shown to confer cytotoxic activity against cancer cell lines.[52] The paramagnetic iron oxide nanoparticles (29 nm) fabricated using *Bacillus cereus* were reported to show anti-cancer effects in a dose-dependent manner. Other magnetic nanoparticles like Fe_3O_4 (magnetite) and Fe_2O_3 (maghemite) have been actively investigated for targeted cancer treatment, stem cell sorting and manipulation, guided drug delivery, gene therapy, DNA analysis, tissue repair, cell labeling, targeting and immunoassays, detoxification of biological fluids and magnetic resonance imaging.[53,54] The Au NPs synthesised using *Lyngbya majuscule* isolated from the Arabian Gulf were found to act as an anti-myocardial infarction agent in combination with *Lyngbya majuscule*.[55] Gold NPs have been studied extensively for their application in specific delivery of drugs, tumour detection, angiogenesis, genetic disease and genetic disorder diagnosis, photo imaging and photo thermal therapy.[56] Significant usage of zinc and titanium NPs in biomedical, cosmetic, ultraviolet (UV)-blocking agents, and various cutting-edge processing applications can be attributed to their biocompatible, nontoxic, self-cleansing, skin-compatible, antimicrobial, and dermatological behaviours.[57,58]

Metal-reducing microbes act as geochemical agent since they play vital role in promoting the transformations, precipitations and dissolutions of minerals.[59] Very interestingly, the metal reducing microbes exhibiting extracellular electron transfer mechanism are suggested to have implications in electro-microbiological applications for renewable energy.[25] Bacteria-based controlled synthesis of hollow porous silver NPs attract more interest since they show great application potentials in catalysts, Surface Enhanced Raman Scattering (SERS), photo electronic devices, antimicrobial agents, gas adsorption etc.[17] Combination of microbial physiology, metabolic and genetic engineering tools can offer innovative bio-based sustainable method for NPs synthesis.

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References

1. Laurent S, Forge D, Port M, Roch A, Robic C, Vander Elst L et al., Magnetic iron oxide nanoparticles: synthesis, stabilization, vectorization, physicochemical characterizations, and biological applications. Chem Rev. 2010; 108(6): 2064-110.

2. Tiwari JN, Tiwari RN, Kim KS. Zero-dimensional, one dimensional, two dimensional and three-dimensional nanostructured materials for advanced electrochemical energy devices. Prog Mater Sci. 2012; 57: 724-803.

3. Shin WK, Cho J, Kannan AG, Lee YS, Kim DW. Cross-linked composite gel polymer electrolyte using mesoporous methacrylate-functionalized SiO2 nanoparticles for lithium-ion polymer batteries. Sci Rep. 2016; 6: 26332.

4. Hong NH. Introduction to Nanomaterials: Basic Properties, Synthesis and Characterization. Nano-sized Multifunctional Materials Copyright © 2019 Elsevier Inc.

5. Singh P, Kim YJ, Zhang D, Yang DC. Biological Synthesis of Nanoparticles from Plants and Microorganisms.Trends Biotechnol. 2016; 34:588-99.

6. Iravani, S. Green synthesis of metal nano particles using plants. Green Chem. 2011; 13: 2638.

7. Zhang X, Lai Z, Liu Z, Tan C, Huang Y, Li Bet al., A facile and universal top-down method for preparation of mono disperse transition-metal dichalcogenide nano dots. Angew Chemie Int Ed. 2015; 54: 5425-28.

8. Liu D, Li C, Zhou F, Zhang T, Zhang H, Li X et al., Rapid synthesis of mono disperse Aunanospheres through a laser irradiation -induced shape conversion, self-assembly and their electromagnetic coupling SERS enhancement. Sci Rep. 2015; 5: 7686.

9. Zhou Y, Dong CK, Han L, Yang J, Du X W. Top down preparation of active cobalt oxide catalyst. ACS Catal. 2016; 6: 6699-6703.

10. Priyadarshana G, Kottegoda N, Senaratne A, de Alwis A,Karunaratne V. Synthesis of magnetite nanoparticles by top-down approach from a high purity ore. J Nanomater. 2015; 1-8.

11. Jha A K, Prasad K, Prasad K and Kulkarni A R. Plant system: Nature's nano factory. Coll Surf B: Bio interf. 2009; 73: 219-223.

12. Manoj D, Saravanan R, Santhanalakshmi J, Agarwal S, Gupta V K, Boukherroub R. Towards green synthesis of monodisperse Cu nanoparticles: An efficient andhigh sensitive electrochemical nitrite sensor. Sens Actuat B. 2018; 266: 873-82.

13. Slawson RM, Van Dyke MI, Lee H, Trevors JT. Germanium and silver resistance, accumulation and toxicity in microorganisms. Plasmid.1992; 27:72-9.

14. Ali J, Alic N, Wanga L, Waseem H, Pana G. Revisiting the mechanistic pathways for bacterial mediated synthesis of noble metal nanoparticles. J Microbiol Methods. 2019; 159: 18-25.

15. Verma A, Gautam SP, Bansal KK, Prabhakar N, Rosenholm JM. Green Nanotechnology: Advancement in Phytoformulation Research. Medicines (Basel). 2019; 6(1):39.

16. Narayanan KB, Sakthivel N. Biological synthesis of metal nanoparticles by microbes. Adv Colloid Interf Sci. 2010; 156(1-2): 1-13.

17. Hulkoti N I, Taranath T. Biosynthesis of nanoparticles using microbes-A review. Colloids Surf B. 2014; 121: 474-83.

18. Thakkar KN, Mhatre SS, Parikh RY. Biological synthesis of metallic nanoparticles. Nanomedicine. 2010; 6(2):257-62.

19. Shahverdi AR, Minaeian S, Shahverdi HR, Jamalifar H, Nohi AA. Rapidsynthesis of silver nanoparticles using culture supernatants of Enterobacteria: a novel biological approach. Process Biochem. 2007; 42(5): 919-23.

20. Nair B, Pradeep T. Coalescence of nanoclusters and formation of submicron crystallites assisted by Lactobacillus strains. Cryst Growth Des. 2002; 2(4):293-8.

21. Arshad A. Bacterial Synthesis and Applications of Nanoparticles. Nano Sci Nano Technol. 2017;11:119

22. Klaus T, Joerger R, Olsson E, Granqvist CG. Silver-Based Crystalline Nanoparticles, Microbially Fabricated, Proc Natl Acad Sci USA.1999; 96(4): 13611-14.

23. Mukherjee P, Senapati S, Mandal D, Ahmad A, Khan MI, Kumar R et al.Extracellular synthesis of gold nanoparticles by the fungus Fusarium oxysporum. ChemBioChem.2002; 3(5): 461-63.

24. He S, Guo Z, Zhang Y, Zhang S, Wang J, Gu N. Biosynthesis of gold nanoparticles using the bacteria Rhodopseudomonas capsulate. Mater Lett. 2007; 61: 3984-87.

25. Ali J, Sohail A, Wang L, RizwanHaider M, Mulk S, Pan G, Electro-microbiology as a promising approach towards renewable energy and environmental sustainability. Energies. 2018; 11(7): 1822.

26. Marooufpour N, Alizadeh M, Hatami M and Lajayer B A. Biological Synthesis of Nanoparticles by Different Groups of Bacteria. Microbial Nanobionics, Nanotechnology in the Life Sciences © Springer, Nature Switzerland, 2019.

27. Khan I, Saeed K, Khan I. Nanoparticles: Properties, applications and toxicities. Arab J Chem.2019; 12(7): 908-31.

28. Beveridge T J and Murray R G E. Sites of metal deposition in the cell wall of

Bacillus subtilis. J Bacteriol. 1980; 141(2):876-87.

29. Joerger R, Klaus T and Granqvist C G. Biologically produced silver-carbon

composite materials for optically functional thin film coatings. Adv Mater. 2000; 12:407-9.

30. Kalimuthu K, Babu RS, Venkataraman D, Bilal M, Gurunathan S. Biosynthesis of silvernanocrystals by Bacilluslicheniformis. Colloids Surf B Biointerfaces. 2008; 65:150-3.

31. Kaur H, Dolma K, Kaur N, Malhotra A, Kumar N, Dixit P et al.,Marine microbe as nano-factories for copper biomineralization. Biotechnol Bioprocess Eng. 2015; 20:51-7.

32. Selvarajan E, Mohanasrinivasan V. Biosynthesis and characterization of ZnO nanoparticles usingLactobacillus plantarum VITES07. Mater Lett. 2013; 112: 180-2.

33. Jayaseelan C, Rahuman AA,Kirthi AV,Marimuthu S, Santhoshkumar T, BagavanAet al., Novel microbial route to synthesize ZnO nanoparticles using Aeromonas hydrophila and their activity against pathogenic bacteria and fungi. Spectrochim Acta A Mol Biomol Spectrosc. 2012; 90: 78-84.

34. Rad M, Taran M, Alavi M. Effect of Incubation Time, CuSO4 and Glucose Concentrations on Biosynthesisof Copper Oxide (CuO) Nanoparticles with Rectangular Shape and Antibacterial Activity: Taguchi MethodApproach. Nano Biomed Eng. 2018; 10: 25-33.

35. Arakaki A, Nakazawa H, Nemoto M, Mori T, Matsunaga T. Formation of magnetite by bacteria and its application. J R Soc Interface. 2008; 5(26): 977-99.

36. Perez-Gonzalez T, Valverde-Tercedor C, Yebra-Rodriguez A, Prozorov T, Gonzalez-Muñoz M T, Arias-Peñalver J M, Jimenez-Lopez C. Chemical purity of Shewanellaoneidensis-induced magnetites. Geomicrobiol J. 2013; 30: 731-48.

37. Du L, Jiang H, Xiaohua L and Wang E. Biosynthesis of gold nanoparticles assisted by Escherichiacoli DH5α and its application on direct electrochemistry of hemoglobin. Electrochem Commun.2007; 9:1165-70.

38. Cunningham DP, Lundie L. Precipitation of cadmium by Clostridium thermoaceticum. Appl Environ Microbiol.1993; 59(1):7-14.

39. Sweeney RY, Mao C, Gao X, Burt JL, Belcher AM, Georgiou G, Iverson BL. Bacterialbiosynthesis of cadmium sulfidenanocrystals. J Chem.2004; 1(11)1:1553-9.

40. Oremland RS, Herbel MJ, Blum JS, Langley S, Beveridge T J, Ajayan P M et al. Structural and spectral features of selenium nanospheres produced by Se-respiring bacteria. Appl Environ Microbiol. 2004; 70:52-60.

41. Dobias J, Suvorova EI, Bernier-Latmani R. Role of proteins in controlling selenium nanoparticle size. Nanotechnology. 2011; 22(19):195605.

42. Prasad K, Jha AK, Kulkarni A. Lactobacillus assisted synthesis of titanium nanoparticles. Nanoscale Res Lett. 2007; 2(5):248-50.

43. Sharma N, Pinnaka AK, Raje M, Ashish F, Bhattacharyya MS, Choudhury AR. Exploitation of marine bacteria for production of gold nanoparticles. Microb Cell Factories. 2012;11:86

44. Lee S Y. High cell-density culture of Escherichiacoli. Trends Biotechnol. 1996; 14(3):98-105.

45. Khan MZH, Tarek FK, Nuzat M, Momin MA, Hasan MR. Rapid Biological Synthesis of Silver Nanoparticles from Ocimumsanctum and Their Characterization. J Nanosci. 2017; Article ID 1693416, 6 pages.

46. Varshney R, Bhadauria S, Gaur M, Pasricha R. Copper nanoparticles synthesis from electroplating industry effluent. Nano Biomed Eng. 2011; 3(2):115-9.

47. Konishi Y, Ohno K,Saitoh N, Nomura T, Nagamine S. Microbial synthesis of gold nanoparticles by metal reducing bacterium. Trans Mater Res Soc Jpn. 2004; 29:2341-3.

48. Sintubin L, De Windt W, Dick J, Mast J, van der Ha D,Verstraete W et al.Lactic acid bacteria as reducingand capping agent for the fast and efficient production of silver nanoparticles. Appl Microbiol Biotechnol. 2009; 84(4):741-9.

49. Prasad R, Pandey R, Barman I. Engineering tailored nanoparticles with microbes: quo vadis. WIREs Nanomed Nanobiotechnol. 2016; 8(2):316-30.

50. Birla S S, Tiwari V V, Gade A K, Ingle A P, Yadav A P, Rai M K. Fabrication of silver nanoparticles by Phomaglomerata and its combined effect againstEscherichia coli, Pseudomonas aeruginosa and Staphylococcus aureus. Lett Appl Microbiol. 2009; 48(2):173-9.

51. Fayaz M, Balaji K, Girilal M, Yadav R, Kalaichelvan PT and Venketesan R. Biogenic synthesis of silver nanoparticles and its synergetic effect with antibiotics:a study against Gram positive and Gram negative bacteria. Nanomedicine.2010; 6(1):103-9.

52. Ahamed M, AlSalhi MS, Siddiqui M. Silver nanoparticle applications and human health. Clin Chim Acta.2010; 411:1841-8.

53. Matsunaga T, Takeyama H. Biomagnetic nanoparticle formation and application. Supramol Sci. 1998; 5:391-4.

54. ArbabAS, Bashaw LA, Miller BR, Jordan EK, Lewis B K, Kalish H et al. Characterization of biophysical and metabolic properties of cells labelled with super paramagnetic ironoxide nanoparticles and transfection agent for cellular MR imaging. Radiology. 2003; 229:838-46.

55. Bakir E, Younis N, Mohamed M, Semary N. Cyanobacteria as Nanogold Factories: Chemical andAnti-Myocardial Infarction Properties of Gold Nanoparticles Synthesized by Lyngbyamajuscula. Mar Drugs. 2018; 16(6): 217.

56. Rai M, Ingle AP, Birla S, Yadav A, Santos CAD. Strategic role of selected noble metalnanoparticles in medicine. Crit Rev Microbiol. 2016;42(5):696-719.

57. Khalil AT, Ovais M, Ullah I, Ali M, Shinwari ZK, Khamlich S et al. M.Sageretiatheamediated synthesis of zinc oxide nanoparticles and its biological applications. Nanomedicine. 2017; 12(15): 1767-89.

58. Ovais M, Khalil A T, Ayaz M, Ahmad I,Nethi S K, Mukherjee S. Biosynthesis of Metal Nanoparticles via MicrobialEnzymes: A Mechanistic Approach. Int J Mol Sci. 2018; 19(12): 4100.

59. Diaz MR, Swart PK, Eberli GP, Oehlert AM, Devlin Q, Saeid A et al.Geochemical evidence of microbial activity within ooids. Sedimentology. 2015; 62: 2090-2112.