Different strategies to synthesise gold nanoparticles and their applications

Fatima Javeria, Shazma Altaf, Alishah Zair and Rana Khalid Iqbal*

Institute of Molecular Biology and Biotechnology,
Bahauddin Zakariya University,
Multan 60800, Pakistan
Email: fatimajaved524@gmail.com
Email: shazmamalik04@gmail.com
Email: Alishazair101@gmail.com
Email: khalid.iqbal@bzu.edu.pk
*Corresponding author

Abstract: Nanotechnology is a science which deals with particles in the nanometre size range. They made from different metals such as copper, silver, zinc, gold, platinum etc. Gold nanoparticles have been synthesised at large scale due to their wide applications in diagnostics, treatment, food safety and forensic areas. Nanoparticles are synthesised using different strategies such as chemical synthesis, biogenic synthesis and via biological sources like plants, bacteria, algae, fungi. They are used because of their low toxicity and biocompatibility. Chemical synthesis methods have problems like toxicity so the stimulus of synthesis has shifted from physical and chemical processes towards 'green' chemistry and bioprocesses. Use of plant extracts has been increased widely for synthesis of gold nanoparticles. Microorganisms like bacteria, yeast, fungi, algae and blue green algae have been used mainly for synthesising gold nanoparticles.

Keywords: biosynthesis; AuNPs; plant extract; diagnostics.

Reference to this paper should be made as follows: Javeria, F., Altaf, S., Zair, A. and Iqbal, R.K. (2020) 'Different strategies to synthesise gold nanoparticles and their applications', *Int. J. Biomedical Nanoscience and Nanotechnology*, Vol. 4, Nos. 1/2, pp.70–79.

Biographical notes: Fatima Javeria is an MSc student at Institute of Molecular Biology and Biotechnology Bahauddin Zakariya University, Multan-60800, Pakistan.

Shazma Altaf is an MSc student at Institute of Molecular Biology and Biotechnology Bahauddin Zakariya University, Multan-60800, Pakistan.

Alishah Zair is an MSc student at Institute of Molecular Biology and Biotechnology Bahauddin Zakariya University, Multan-60800, Pakistan.

Rana Khalid Iqbal is an Assistant Professor at the Institute of Molecular Biology and Biotechnology Bahauddin Zakariya University, Multan-60800 Pakistan.

1 Introduction

Nanotechnology is an attractive field of science interconnected with various other fields of science. Nanotechnology is concerned with the application of 0.1–100 nm sized materials. Materials of nano size have completely different properties as compared to its native size or its abundant form. Nanoparticles hold great importance in the scientific world because they are capable of combining bulk materials and molecular constructs (Pacheco-torgal and Jalali, 2015). Nanoparticles are formed when 1 g of gold is transformed to nanoscale particles, which have the ability of expanding over an area of 100 km^2 (Buffat and Borel, 1976). Several attractive properties of gold nanoparticles (AuNPs) have made them more important in the past. AuNPs have strong surface plasmon, catalytic behaviour, redox activity, due to this reason it has been widely used over the past few years. These AuNPs are widely used in medicinal diagnostics, imaging, optical, and forensic areas (Han et al., 2013). Gold is a valuable, biocompatible metal. In ancient times, colloidal gold was used as a drinkable solution for its therapeutic properties for several diseases (Daniel and Astruc, 2004).

For the economical, energy-efficient, and nontoxic production of AuNPs, many bio-mimic processes, utilising plants, algae, fungi, bacteria, and yeast, have been used. Various approaches which includes the employment of external chemical reductants such as sodium citrate or $NaBH_4$ which reduces tetrachloroauric acid to produce AuNPs, are known for the production of various unwanted side products which are the cause of nanoparticles contamination. Herein, there are various functionalising agents being recently introduced which acts as a potent reducing agent as well as an effective stabiliser for AuNPs (Khan et al., 2013). The AuNPs have broad range of applications in the field of biomedicine, catalysis and photoelectronic materials. Nanomaterial technology is aimed at producing metal nanoparticles for accomplishing their many applications in the field of biology, photonics and in the production of sensor devices. Due to antibacterial properties and large surface area to volume ratio and biocompatibility, nanoparticles are considered as most promising for various purposes e.g., cancer and arthritis treatment (Ahmed et al., 2016).

2 Synthesis

2.1 Chemical methods

In order to obtain different shapes of semiconducting systems, high temperature solution methods were used. Two different colloid chemical synthetic protocols were used (Chen et al., 2003). They formed mixture of branched gold nanoparticles. From rod to branched structures were formed by the solution based chemical route. This method produces high yield of Au particles at room temperature. Au particles were formed in the presence of a single surfactant in aqueous solution. Au particles were synthesised by preparing aqueous growth solutions with the combination of CTAB, $HAuCl_4$, ascorbic acid with subsequent addition of small quantities of $AgNO_3$. Monodispersed Au nanoparticles were produced by adjusting the concentrations of all the four reactants. Hexagonal and cubic nanoparticles were produced in very high yield about 90% at room temperature (Sau and Murphy, 2004).

2.1.1 Synthesis of octahedral gold nanoparticles

One pot, non-seeding method was used to prepare gold octahedral nanoparticles at room temperature, it successfully prepares gold octahedral nanoparticles in a very high yield. High concentration of CTAB produces octahedral nanoparticles whereas in the high concentration of CTAB, ascorbic acid reduces $HAuCl_4$. Moreover, CTAB acts as a stabilising and templating surfactant whereas ascorbic acid acts as a reducing agent which reduces CTAB-Au^{3+} complex to Au^+. Due to the fact, both CTAB and ascorbic acid are extensively employed for the synthesis of various shapes of gold nanoparticles. Au seeds are widely used for the reduction of Au^+ to Au^0 (Johnson et al., 2002). Threshold energy of the reaction was decreased by the Au seeds i.e., Au seeds act as catalysts for the growth of particles. Gold nanoparticles are hardly to be produced without Au seeds especially in the densely surfactant-containing solution. Ascorbic acid is a mild reductant due to which low concentration and slow growth kinetics of the colloidal particles were observed while the process was not catalyzed by any pre-synthesised Au seeds. When a small amount of H_2O_2 was added to the reaction it produces high yield Au octahedral particles. H_2O_2 is a strong oxidising agent and it can also reduce gold ions to synthesise AuNPs. Activation of reduction-oxidation reactions of ascorbic acid is done by H_2O_2 rather than reduction of $HAuCl_4$ (Cao et al., 2008).

2.2 Biological methods

The impetus of synthesis has shifted from physical and chemical processes towards ‘green’ chemistry and bioprocesses (Vigneshwaran et al., 2007). Toxic chemicals are not used for biosynthesis of gold nanoparticles so, it is environmentally safe. Gold nanoparticles can be synthesised by the extracts of biological systems e.g., microbes, plant, fungi and microbe extracts (Tiwari et al., 2011).

2.2.1 From plants

Plants parts are taken, cut and washed for the synthesis of gold nanoparticles for the production of nanoparticles from plant source material. Extract is obtained by boiling of plant parts in water. With the purification of extract is done by centrifugation and filtration. For the production of gold nanoparticles gold salt is used under different conditions of temperature and pH in different ratios. For the conversion of auric salt solutions into gold nanoparticles it is mixed with extract at 25 Celsius. There is no need for the addition of stabilising agents because phytochemicals are reducing agents. Change in colour is visualised when the reaction mixture is incubated and is converted into metal salts. These can be separated by filtration and centrifugation and can be used for further use (Ahmed et al., 2016).

Use of plant extracts is getting common due to their eco friendliness and these processes can also be suitable for large scale synthesis of NPs. The use of environmentally benevolent plant material suggested massive advantages of Eco friendliness and suitability for biomedical and pharmaceutical applications (Govindaraju et al., 2011).

Neem leaf broth is used to synthesise gold NPs. The reduction of sugar and terpenoids in the neem leaf broth make the formation of pure metallic nanoparticles possible (Shankar et al., 2004). Geranium leaves and lemon grass extract are used to synthesise AuNPs (Shankar et al., 2004). Tamarind leaf extract is used for the synthesis for Au nanorods (Taylor et al., n.d.). AuNPs are synthesised within live alfalfa plants and this technique can be very proficient in the decontamination of soil contaminated with heavy metal ions (Parsons et al., 2002). Magnolia kobus and Diopyros kaki leaf extracts are used for the rapid synthesis of AuNPs (Song et al., 2009). Tea leaves were used to synthesise gold nanoparticles (Nune et al., 2009). For the formation of gold nanoparticles, a source for phytochemical reservoir is soybeans (Shukla et al., 2008). For the rapid synthesis of gold nanoparticles, banana peel extract is an efficient material.

Seasonal variations affect the synthesis of nanoparticles by using leaf extract. Horse gram (*M. uniflorum*) is sovereign crop of seasonal variations. Horse gram is a dry land legume crop which grows mainly on the lands where it is difficult to grow crops. Different parts of this plant are used for the treatment of heart disorders, respiratory disorders, urinary systems disorder, etc. To control cholesterol level of human body, a water soup of horse gram is effective. Phenolic compounds serve as reduction power for nanostructure (Chavan et al., 2010) so, the choice of plant material is dependent in the presence of cholesterol in the plant. Phenolic contents serve as an antioxidant which helps to reduce gold cations to AuNPs. This is an easy, inexpensive, safe and effective technique to synthesise gold NPs (Aromal et al., 2012).

2.2.2 From microbes

Micro-organisms can be used for biosynthesis of gold nanoparticles either extracellularly or intracellularly. Extracellular method is most popular as it eliminates various processing steps required for recovery of gold nanoparticles. In extracellular biosynthesis, after the subculture of micro-organisms for 1–2 days, the culture is centrifuged to remove the biomass. The gold nanoparticles can be synthesised by adding supernatant to auric salt solution. The gold nanoparticles synthesis can be monitored by change in colour of culture media from ruby red to deep purple colour. After bio reduction, the gold nanoparticles can be collected by similar methodologies as in plant extract mediated synthesis. Synthesis of gold nanoparticles using biogenic agents (plants and micro-organisms) is an eco-friendly method and this method requires only a short period for the conversion of metal ions into nanoparticles (Ahmed et al., 2016).

Such microorganisms have recognised which are eco-friendly. Gold nanoparticles are synthesised by microorganisms because microbes have a great potential for productions of NPs (Mukhopadhyay and Sarkar, 2006). Microbes like yeast, bacteria, and fungi are being widely used in the biosynthesis of AuNPs because microbes have a great potential to reduce toxic metals under stress conditions so they play a vital role in the remediation of toxic metals. Metal ions are reduced to metals by various microbes (Sastry et al., 2003). The process of active metal conversion is speeded up if the enzymes are present in compatible microbes. The microorganisms undoubtedly play a vital role in providing assembly of nucleation centres. The condition for a highly disperse nanoparticles system is achieved by microbes. The microbes slow down or avoid collection by providing a viscous medium (Melillo et al., 2002).

2.2.2.1 From bacteria

Magnetite nanoparticles are prepared by magneto-tactic bacteria (Lowenstam, 1981) and gypsum and calcium carbonate layers are prepared by S-layer bacteria (Pum and Sleytr, 1999).

Methanotrophs are a group of Gram-negative bacteria. Methanotrophs use methane as energy source. Methanotrophs use methane monooxygenase enzyme to oxidise methane. Copper regulates the activity of methane monooxygenase (Hanson and Hanson, 1996). Methanobactin (Mb) is secreted by methanotrophs. Methanobactin is a small, copper-binding peptide. Methanobactin extracts and uptakes copper outside the bacterial cell (Balasubramanian and Rosenzweig, 2008). A number of metals such as gold, iron, nickel, zinc, cobalt, cadmium,mercury and uranium can also be fixed with Mb. Au(III) can be reduced to Au(0), and Au(0) remains attached with the Mb. By transmission electron microscopy (TEM) the examination of Au-Mb complexes shows very little to zero detection of nanoparticles. Gold nanoparticles were observed if Au-Mb sample solutions were centrifuged or exposed to one freeze thaw cycle (Choi et al., 2006). For the preparation of monodispersed gold nanoparticles, a one-step synthetic scheme is used. It is demonstrated that gold nanoparticles can be rapidly formed if hydroquinone is provided as a reductant. Mb is responsible for the catalysed reduction of Au(III) and the stabilisation of gold nanoparticles. By adjusting the ratio of Au(III) to Mb in solution the size can be tuned. The nanoparticles formed are homogeneous, spherical in shape. The nanoparticles will not aggregate and remain stable even after several months (Xin et al., 2013).

2.2.2.2 From fungi

By using *Aspergillus niger* NCIM 616 extracellular biosynthesis of stable AuNPs was done. This fungus was previously used in submerged fermentation for the production of squalene. Gold nanoparticles were stabilised by the secretion of proteins in aqueous filtrate. The bio-synthesis of nanoparticles has advantage over other methods presently in use. Nanoparticles have great advantage due to their relative stability in the solution. This study paved the way towards the production of a simple bioprocess for the synthesis of AuNPs (Bhambure et al., 2009).

Use of fungal systems in extracellular biosynthesis of AuNPs has advantages like homogeneous catalysis and non-linear optics. This fungal system is free from any harmful chemicals or solvents. There are various parameters for the production of AuNPs, however, the important parameters include pH and temperature (Sanghi and Verma, 2009).

The production of AuNPs was confirmed by visual monitoring. Three different solutions of fermented filtrate of *Aspergillus niger* NCIM616 in aqueous form, $AuCl_3$ solution, and reaction mixture of the aqueous filtrate with $AuCl_3$ were employed for the synthesis of gold nanoparticles (Bhambure et al., 2009).

A change in the original colour of mixed supernatant of auric chloride (fungal aqueous filtrate and the $AuCl_3$ solution) into dark purple after incubation for 24 hours was observed. The dark purple colour in solution is a conformation of the production of AuNPs (Underwood and Mulvaney, 1994).

2.2.2.3 From algae and blue green algae

Algae have the advantage over other microorganisms due to high resistance under severe environmental conditions. The synthesis of AuNPs from algae takes place under normal conditions in water which is environmentally friendly and economical, because any poisonous chemicals are not the part of AuNPs synthesis. The various advantages of AuNPs synthesis using algae include simplicity, low cost, cleanliness, non-poisonous and environmentally friendly nature (Khan et al., 2018). AuNPs were produced from algae *Chlorella vulgaris* (Ting et al., 1995), *Sargassum wightii* (Singaravelu et al., 2007) *and Plectonemaboryanum* (Lengke et al., 2006). The production of AuNPs involves the exploitation of aqueous filtrate of marine algae *Gracilariacorticata* which acts as a reducing agent. The results were confirmed by the use of UV-visible spectroscopy and scanning electron microscopy (Synthesis et al., 2013).

By interacting *Sargassum muticum* extract, the green biosynthesis of AuNPs was done. This method reported in vitro anticancer activity in human leukemia cell lines (Namvar et al., 2015). Green algae *Pithophoraoedogonia* was used as reducing agent for the biosynthesis of AuNPs. During this method, Au salts interact with algal extract within one hour in the formation of AuNPs. They showed admirable electrolytic activity towards the determination of carbendazim in soil (Li and Zhang, 2016). Red seaweed *porphyran* was used as a reducing agent for the one pot, size-controlled biosynthesis of AuNPs. *Porphyran* is derived from red algae of the porphyra. It is a sulphated carbohydrate. The manufactured AuNPs were used as a vehicle for the delivery of an anticancer drug. For the controlled biosynthesis of AuNPs, *Porphyrin* was used as a reducing agent and has biological potential as a vehicle for the delivery of anticancer drug (Venkatpurwar et al., 2011).

3 Applications

Applications of AuNPs have become widespread in several fields like pharmaceuticals, biomedical, catalysis, drug delivery and antimicrobial etc. due to their enhanced properties.

3.1 In cancer diagnostics

Lipid and polymeric nanoparticles encapsulate the therapeutic molecule to increase drug solubility. Due to the fast and simple preparation and bio conjugation, AuNPs are most important. Gold nano-spheres are prepared by reduction of auric acid with sodium citrate. Gold nanorods are developed by gold ionisation and reduction. Due to the enhanced optical property they are used in cancer therapy and phototherapy. The molecular specific cancer can be detected and diagnosed by using gold nanoparticles. Light scattering imaging, two-photon luminescence imaging, and plasmonic photo-thermal therapy etc. AuNPs have light scattering property and due to this they are used in cancer therapy. Expose that molecularly targeting to cancer tissues done by conjugation with anti-epidermal growth factor receptors antibodies (Tiwari et al., 2011).

3.2 *Food safety screening*

The gold nanoparticles due to their physiochemical properties are used in food safety screening technologies by forming covalent and non-covalent bonds with target substance. Calorimetric sensors based on gold nanoparticles have high sensitivity and are widely applied in real time on-site monitoring for food quality and safety (Liu et al., 2018).

3.3 *In gene delivery*

The problems facing during viral vectors thus now can be solved by using non-viral systems as metallic nanoparticles. AuNPs of different shapes protect the nucleic acid by protecting DNA and RNA from degradation by nuclease. AuNPs by forming conjugation with oligonucleotides make potential gene regulatory system.

3.4 *In agri-food*

Nanosensors are used to check the quality of food products and in bacteria identification. In 2004 through the cellular injection the rice colour changed cellular injection with carbon nanofibres having DNA used to genetically modify rice to increase food production, and phytomedicine content in fruits the based nanoparticle fullerol ($C_{60}(OH)_{20}$) used as causal factor. Metals (palladium, gold and platinum) are used as nanobiosensors in agricultural food production. This is to extract gold from a crop such as alfalfa grown in $AuCl_4$ through which the plant absorbs gold metal.

3.5 *In poultry production*

Gold nanoparticle-based diagnosis kits locate influenza virus by using nanotechnology so the poultry production becomes safe and faster. Nanobiotic silver has antimicrobial property in poultry.

References

Ahmed, S., Annu, Ikram, S. and Yudha, S.S. (2016) 'Biosynthesis of gold nanoparticles: a green approach', *Journal of Photochemistry and Photobiology B Biology*, Vol. 161, pp.141–153 [online] https://doi.org/10.1016/j.jphotobiol.2016.04.034 (accessed 15 May 2019).

Aromal, S.A., Vidhu, V.K. and Philip, D. (2012). Spectrochimica acta part A: molecular and biomolecular spectroscopy green synthesis of well-dispersed gold nanoparticles using macrotyloma uniflorum', *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, Vol. 85, No. 1, pp.99–104 [online] https://doi.org/10.1016/j.saa.2011.09.035 (accessed 4 May 2019).

Balasubramanian, R. and Rosenzweig, A.C. (2008) *Copper Methanobactin: A Molecule Whose Time Has Come*, pp.245–249 [online] https://doi.org/10.1016/j.cbpa.2008.01.043 (accessed 2 June 2018).

Bhambure, R., Bule, M., Shaligram, N., Kamat, M. and Singhal, R. (2009) 'Extracellular biosynthesis of gold nanoparticles using Aspergillus niger – its characterization and stability', *Chemical Engineering and Technology*, Vol. 32, No. 7, pp.1036–1041 [online] https://doi.org/10.1002/ceat.200800647 (accessed 20 November 2018).

Cao, C., Park, S. and Jun, S. (2008) 'Seedless synthesis of octahedral gold nanoparticles in condensed surfactant phase', Vol. 322, pp.152–157 [online] https://doi.org/10.1016/j.jcis.2008.03.031 (accessed 4 May 2019).

Chavan, U.D., Phule, M., Vidyapeeth, K., Kadam, S. and Amarowicz, R. (2010) 'Isolation and characterization of starch from horse gram', *African Journal of Food Science and Technology*, January, Vol. 1, No. 3, pp.064–067.

Chen, S., Wang, Z.L., Ballato, J., Foulger, S.H. and Carroll, D.L. (2003) 'Monopod, bipod, tripod, and tetrapod gold nanocrystals', *J. Am. Chem. Soc.*, Vol. 125, No. 52, pp.16186–16187.

Choi, D.W., Do, Y.S., Zea, C.J., Mcellistrem, M.T., Lee, S., Semrau, J.D., … Dispirito, A.A. (2006) 'Spectral and thermodynamic properties of Ag (I), Au (III), Cd (II), Co (II), Fe (III), Hg (II), Mn (II), Ni (II), Pb (II), U (IV), and Zn (II) binding by methanobactin from Methylosinus trichosporium OB3b', *J. Inorg. Biochem*., Vol. 100, pp.2150–2161 [online] https://doi.org/10.1016/j.jinorgbio.2006.08.017 (accessed 7 June 2019).

Daniel, M. and Astruc, D. (2004) 'Gold nanoparticles: assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology', *Chem. Rev*., Vol. 104, No. 1, pp.293–346.

Govindaraju, K., Kiruthiga, V., Manikandan, R., Ashokkumar, T. and Singaravelu, G. (2011) β-glucosidase assisted biosynthesis of gold nanoparticles: a green chemistry approach', *Materials Letters*, Vol. 65, No. 2, pp.256–259 [online] https://doi.org/10.1016/j.matlet.2010.09.078 (accessed 25 May 2019).

Han, T.H., Khan, M.M. and Kalathil, S. (2013) 'Synthesis of positively charged gold nanoparticles using a stainless-steel mesh', *Journal of Nanoscience and Nanotechnology*, Vol. 13, No. 9 [online] https://doi.org/10.1166/jnn.2013.7660 (accessed 23 May 2019).

Hanson, R.S. and Hanson, T.E. (1996) 'Methanotrophic macteria', *Microbiol Rev.*, Vol. 60, No. 2, pp.439–471.

Buffat, P. and Borel, J-P. (1976) '1976 size effect', *Physical Review A*, Vol. 13, No. 6, pp.2287–2298 [online] https://sci-hub.tw/10.1103/PhysRevA.13.2287.

Johnson, C.J., Dujardin, E., Davis, S.A., Murphy, J. and Mann, S. (2002) 'Growth and form of gold nanorods prepared by seed-mediated, surfactant-directed synthesis', *Journal of Materials Chemistry*, pp.17–21 [online] https://doi.org/10.1039/b200953f (accessed 21 May 2019).

Khan, A.U., Khan, M., Malik, N., Hwan, M., Mohammad, C. and Khan, M. (2018) 'Recent progress of algae and blue – green algae-assisted synthesis of gold nanoparticles for various applications', *Bioprocess and Biosystems Engineering* [online] https://doi.org/10.1007/s00449-018-2012-2 (accessed 4 May 2019).

Khan, M.M., Kalathil, S., Han, T.H., Lee, J. and Cho, M.H. (2013) 'Positively charged gold nanoparticles synthesized by electrochemically active biofilm – a biogenic approach', *Journal of Nanoscience and Nanotechnology*, Vol. 13, No. 9, pp.6079–6085 [online] https://doi.org/10.1166/jnn.2013.7666 (accessed 23 May 2019).

Lengke, M.F., Fleet, M.E. and Southam, G. (2006) 'Morphology of gold nanoparticles synthesized by filamentous cyanobacteria from gold (I) – thiosulfate and gold (III) – chloride complexes. (I)', *American Chemical Society*, Vol. 22, No. 6, pp.2780–2787 [online] https://doi.org/10.1021/la052652c.

Li, L. and Zhang, Z. (2016) 'Biosynthesis of gold nanoparticles using green alga pithophora oedogonia with their electrochemical performance for determining carbendazim in soil', *Int. J. Electrochem. Sci.*, Vol. 11, p.4559 [online] https://doi.org/10.20964/2016.06.13 (accessed 7 June 2019).

Liu, G., Lu, M., Huang, X., Li, T. and Xu, D. (2018) 'Application of gold-nanoparticle colorimetric sensing to rapid food safety screening', *Sensors*, pp.1–16 [online] https://doi.org/10.3390/s18124166 (accessed 15 May 2019).

Lowenstam, H. A. (1981) 'Minerals formed by organisms', *Science*, Vol. 211, No. 4487, pp.1126–1131 [online] https://doi.org/10.1126/science.7008198.

Melillo, J.M., Bowles, F.P., Melillo, J.M., Steudler, P.A., Rayment, M., Trumbore, S.E., … Currie, W.S. (2002) 'Shape-controlled synthesis of gold and silver nanoparticles', *Science*, Vol. 298, No. 5601, pp.2176–2179 [online] https://doi.org/10.1126/science.1077229.

Mukhopadhyay, D. and Sarkar, G. (2006) 'The use of microorganisms for the formation of metal nanoparticles and their application', *Applied Microbiology and Biotechnology*, pp.485–492 [online] https://doi.org/10.1007/s00253-005-0179-3 (accessed 29 September 2018).

Namvar, F., Rahman, H.S., Mohamad, R., Rasedee, A., Yeap, S.K., Chartrand, M.S., … Tahir, P.M. (2015) 'Apoptosis induction in human leukemia cell lines by gold nanoparticles synthesized using the green biosynthetic approach', *Journal of Nanomaterials*, pp.1–10 [online] https://doi.org/10.1155/2015/642621.

Nune, S.K., Chanda, N., Shukla, R., Katti, K., Kulkarni, R.R., Thilakavathy, S., … Katti, K.V. (2009) 'Green nanotechnology from tea: phytochemicals in tea as building blocks for production of biocompatible gold nanoparticles', *Journal of Materials Chemistry*, pp.2912–2920 [online] https://doi.org/10.1039/b822015h (accessed 25 May 2019).

Pacheco-torgal, F. and Jalali, S. (2015) 'Nanotechnology: advantages and drawbacks in the field of construction and building materials', *Construction and Building Materials*, Vol. 25, No. 2, pp.582–590 [online] https://doi.org/10.1016/j.conbuildmat.2010.07.009 (accessed 23 May 2019).

Parsons, J.G., Gomez, E., Troiani, H.E., Santiago, P. and Yacaman, M.J. (2002) 'Formation and growth of Au nanoparticles inside live alfalfa plants', *Nano Letters*, Vol. 2, No. 4, pp.397–401 [online] https://doi.org/10.1021/nl015673+.

Pum, D. and Sleytr, U.B. (1999) 'The application of bacterial S-layers in molecular nanotechnology', *Trends in Biotechnology*, January, Vol. 17, No. 1, pp.8–12.

Sanghi, R. and Verma, P. (2009) 'Bioresource technology biomimetic synthesis and characterisation of protein capped silver nanoparticles', *Bioresource Technology*, Vol. 100, pp.501–504 [online] https://doi.org/10.1016/j.biortech.2008.05.048 (accessed 29 September 2018).

Sastry, M., Ahmad, A., Khan, M.I. and Kumar, R. (2003) 'Biosynthesis of metal nanoparticles using fungi and actinomycete', *Current Science*, Vol. 85, No. 2, pp.162–170.

Shankar, S.S., Rai, A., Ankamwar, B., Singh, A., Ahmad, A. and Sastry, M. (2004) 'Biological synthesis of triangular gold nanoprisms', *Nature Materials*, Vol. 3, No. 7, pp.482–488 [online] https://doi.org/10.1038/nmat1152.

Sau, T.K. and Murphy, C.J. (2004) 'Room temperature , high-yield synthesis of multiple shapes of gold nanoparticles in aqueous solution', *American Chemical Society*, Vol. 126, No. 28, pp.8648–8649 [online] https://doi.org/10.1021/ja047846d.

Shankar, S.S., Rai, A., Ahmad, A. and Sastry, M. (2004) 'Rapid synthesis of Au, Ag, and bimetallic Au core – Ag shell nanoparticles using Neem (Azadirachta indica) leaf broth. 275', *Journal of Colloid and Interface Science*, 15 July, Vol. 275, No. 2, pp.496–502 [online] https://doi.org/10.1016/j.jcis.2004.03.003 (accessed 25 May 2019).

Shukla, R., Nune, S.K., Chanda, N., Katti, K., Mekapothula, S., Kulkarni, R.R., … Katti, K.V. (2008) 'Green chemistry soybeans as a phytochemical reservoir for the production and stabilization of biocompatible gold nanoparticles', *Green Chemistry*, pp.1425–1436 [online] https://doi.org/10.1002/smll.200800525 (accessed 25 April 2019).

Singaravelu, G., Arockiamary, J.S., Kumar, V.G. and Govindaraju, K. (2007) 'A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga', *Sargassum wightii Greville*, Vol. 57, pp.97–101 [online] https://doi.org/10.1016/j.colsurfb.2007.01.010 (accessed 7 September 2018).

Song, J.Y., Jang, H. and Kim, B.S. (2009) 'Biological synthesis of gold nanoparticles using Magnolia kobus and Diopyros kaki leaf extracts', *Process Biochemistry*, October, Vol. 44, No. 10, pp.1133–1138 [online] https://doi.org/10.1016/j.procbio.2009.06.005 (accessed 25 April 2019).

Synthesis, B., Gold, O. F., Using, N., Algae, M., Application, I.T.S. and Antimicrobial, P. (2013) Biological synthesis of gold nanoparticles using marine algae gracilaria corticata and its application as', Vol. 6, No. 2, pp.4–7.

Taylor, P., Ankamwar, B., Chaudhary, M., Sastry, M. and Ankamwar, B. (n.d.) 'Gold nanotriangles biologically synthesized using tamarind leaf extract and potential application in vapor sensing', *Synthesis and Reactivity in Inorganic, Metal-Organic, and Nano-Metal Chemistry*, May, pp.37–41 [online] https://doi.org/10.1081/SIM-200047527 (accessed 7 November 2018).

Ting, Y.P., Teo, W.K. and Soh, C.Y. (1995) 'Gold uptake by chlorella vulgaris', *Journal of Applied Phycology*, Vol. 7, No. 1, pp.97–100 [online] https://doi.org/10.1007/BF00003557.

Tiwari, P.M., Vig, K., Dennis, V.A. and Singh, S.R. (2011) 'Functionalized gold nanoparticles and their biomedical applications', *Nanomaterials*, Vol. 1, No. 1, pp.31–63 [online] https://doi.org/10.3390/nano1010031 (accessed 2 May 2019).

Underwood, S. and Mulvaney, P. (1994) 'Effect of the solution refractive index on the color of gold colloids', *American Chemical Society*, Vol. 10, No. 3, pp.3427–3430.

Venkatpurwar, V., Shiras, A. and Pokharkar, V. (2011) 'Porphyran capped gold nanoparticles as a novel carrier for delivery of anticancer drug: in vitro cytotoxicity study', *International Journal of Pharmaceutics*, Vol. 409, Nos. 1–2, pp.314–320 [online] https://doi.org/10.1016/j.ijpharm.2011.02.054 (accessed 7 May 2019).

Vigneshwaran, N., Ashtaputre, N.M., Varadarajan, P.V., Nachane, R.P., Paralikar, K.M. and Balasubramanya, R.H. (2007) 'Biological synthesis of silver nanoparticles using the fungus Aspergillus flavus', *Materials Letters*, March, Vol. 61, No. 6, pp.1413–1418 [online] https://doi.org/10.1016/j.matlet.2006.07.042 (accessed 2 May 2019).

Xin, J., Cheng, D., Zhang, L., Lin, K., Fan, H. and Wang, Y. (2013) 'Methanobactin-mediated One-Step Synthesis of gold nanoparticles. (Iii)', *Int. J. Mol. Sci.*, Vol. 14, No. 11, pp.21676–21688 [online] https://doi.org/10.3390/ijms141121676 (accessed 4 May 2019).