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REVIEW ARTICLES

Nanotechnology and it's applications in environmental remediation: an overview

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Abstract

In the last few decades, nanotechnology has come to the fore as a crucial and significant domain in the scientific realm owing to its multidisciplinary nature. The enhanced properties of materials in the nanoscale make them a viable option for different applications in different fields. The conventional method viz. the physical and chemical methods of nanoparticle production, however, pose hazardous risks to the environment. To redress these concerns, researchers have diverted their focus towards the more favourable green method of synthesis which is free from any toxic precursor or strenuous process conditions making it an economical and nature-friendly method. Nanoparticles showed a wide range of application in environmental biotechnology like reduction of pollution, water treatment, remediation, dye degradation and water purification development. This review focuses on the various biogenic precursors for fabrication of nanoparticles and also emphasizes their potential applications in environmental remediation.

Keywords Bioremediation · Dye degradation · Antimicrobial · Green synthesis · Human health

Introduction

The advent of modern technology in tandem with the growing demands of the ever-increasing population has led to a rapid increase in industrialization and urbanization. The consequential strain on the environment is evident and has amplified manifold. The growing need for newer avenues of research in environmental remediation using economically viable and environment friendly techniques has led researchers to the utilization of biosynthetic nanoparticles as a sustainable alternative. Although the use of nanoparticles is an ancient practice which began with the making of coloured glass in Egypt and Mesopotamia dating back to as early as the fourteenth and thirteenth centuries BCE (Schaming and Remita 2015). Nanotechnology refers to the utilization and modification of minute particles of the order of one billionth of a metre (i.e. 10^{-9}) called nanoparticles. Nanoparticles (NPs) can be broadly classified as organic (e.g. carbon based nanoparticle such as fullerene) and inorganic nanoparticles (e.g. metal and metal oxide nanoparticles such as gold, silver, zinc oxide etc.) (Pradhan 2013; Lombardo et al. 2019). Based on their physicochemical characteristics, they can be categorized as Carbon-based NP, Metal NPs, Lipid-based NPs, Semiconductor NPs, Polymeric NPs and Ceramics NPs (Khan et al. 2017; Baranwal et al. 2018). Further depending on their overall shape and dimension, nanoparticles can be sub-divided into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) categories (Pokropivny and Skorokhod 2007).

Nanoparticles have gained immense prominence in the scientific realm owing to the enhanced characteristics of materials in the nanoscale. The high surface-to-volume ratio of nanoparticles which differs from their bulk counterparts increases their reactivity, adsorption and catalytic capacity and makes them great sensors (Khin et al. 2012). These properties make the use of nanoparticles a more viable alternative than other conventional methods of environmental clean-up. In this review, provides a brief overview on various biological methods of nanoparticle synthesis (Plant and microbial based) and their applications for the

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environmental remediation such as dye degradation, heavy metal and hydrocarbon detection and removal.

Different approaches for nanoparticles synthesis

Two general procedural approaches are followed for manufacturing nanoparticles viz. bottom-up approach and top-down approach (Daraio and Jin 2012). Production methods of nanoparticles include primarily the physical, chemical and biological techniques (Iravani et al. 2014). Physical methods generally comprise of physical vapour deposition (Cross et al. 2007), high energy ball milling (de Carvalho et al. 2013), laser ablation (Pyatenko et al. 2004), inert gas condensation (Silva et al. 2014), electrospraying (Quintanilla et al. 2010), laser pyrolysis (Kim et al. 2015) and melt mixing (Lee et al. 2005). However, these methods produces abundant waste during the manufacturing processes makes them less economical (Dhand et al. 2015). Chemical methods of synthesis commonly include polyol synthesis (Meshesha et al. 2009), sol–gel method (Ahlawat et al. 2014), micro-emulsion technique (Chin et al. 2014), hydrothermal synthesis (Khalil et al. 2014a, b) and chemical vapour synthesis (Stijepovic et al. 2015) techniques. Nanoparticles fabricated using the various physical and chemical techniques tend to be expensive and make use of hazardous chemicals which are detrimental to the environment and the living world (Ahmed et al. 2016). Biological synthesis, on the other hand, goes through a paradigm shift in this regard by synthesising nanoparticles using biological precursors through a single step bio-reduction method which consumes less energy and is eco-friendly (Parveen et al. 2016). Further, the reduction of metal ions to their base metal by biochemicals is more rapid and efficient than conventional methods (Taheriniya and Behboodi 2016).

Biogenic synthesis of nanoparticles

There are various methods for the chemical synthesis of silver nanoparticles, but biogenic methods of nanoparticles synthesis offer an alternative to chemical synthesis. Biosynthesis includes use of plant extracts from roots, leaves, fruits, seeds, flowers, latex etc. (Spadaro and Gullino 2005; Song and Kim 2009; Krishnaraj et al. 2010; Saha et al. 2010; Iravani 2011), Bacteria (Lloyd et al. 1998; Shahverdi et al. 2007; Kalimuthu et al. 2008; Narayanan and Sakthivel 2010; Zhang et al. 2011, Schlüter et al. 2014; Javaid et al. 2018), fungi (Ahmad et al. 2003; Shahverdi et al. 2007; Korbekandi et al. 2013; Sandhu et al. 2017) etc. for manufacture of nanoparticles and hence are free from harmful toxic reagents in their production making the procedure sustainable and environmental friendly. Silver nanoparticles have been the theme of researchers because of their distinctive properties (e.g. size, shape and antimicrobial properties). Mainly, there are three major sources of synthesising silver nanoparticles: bacteria, fungi and plant extracts. The perusal of available literature reveals wide application of the biological method for fabrication of nanoparticles in recent years.

Plant-based synthesis of nanoparticles

Plant extract obtained from leaves, flowers, fruits, tubers, roots, latex etc. is a favourable precursor for biogenic production of nanoscale particles because of the presence of different natural plant biomolecules that enable bioreduction of metal ions to their nano form (Makarov et al. 2014). Different plant parts and extracts have been successfully exploited by researchers for preparation of different metallic and metal oxide nanoparticles. Leaf extracts of various plants. There are many report of utilizing plants and its part extract *Aloe vera* (Chandran et al. 2006), *Carica papaya* (Jain et al. 2009), *Tea extract* (Nabikhan et al. 2010), *Nelumbo nucifera* (Santhoshkumar et al. 2011), *Allium sativum* (Ahamed et al. 2011), *Moringa oleifera* (Prasad and Elumalai 2011), *Garcinia mangostana* (Veerasamy et al. 2010), *Vitex negundo* (Zargar et al. 2011), *Acalypha indica* (Kumarasamyraja and jeganathan 2013), *Actaea racemosa* (black cohosh), *Sansevieria trifasciata* and *Impatiens scapiflora* (Okafor et al. 2013), *Alternanthera dentata* (Nakkala et al. 2014a), *Acorus calamus* (Nakkala et al. 2014b), *Boerhavia diffusa* (Suna et al. 2014), *Ziziphora tenuior* (Ulug et al. 2015), *Gelidium amansii* (Pugazhendhi et al. 2018), *Enteromorpha compressa* (Ramkumar et al. 2017), *Phanerochaete chrysosporium* (Saravanan et al. 2018a, b) and *Daucus carota* (Shanmuganathan et al. 2018), *Salvia spinosa* (Pirtarighat et al. 2019) for the biosynthesis of Ag NPs and investigated their antimicrobial properties. Aqueous extract of the *Mangifera Indica* (Mango) leaves reduced Au^{3+} to Au^0 to produce gold nanoparticles at room temperature (Muralikrishna et al. 2014). Stable silver nanoparticles were fabricated from the aqueous extracts of endemic-medicinal plant *Buddleja globosa hope* ("Matico") in a one-step at room temperature and low concentrations of leaf extracts of *B. globosa*, and silver nitrate salt were sufficient to biosynthesize AgNPs with uniform size (16 nm) and shape distribution (spherical) (Carmona et al. 2017). Stable nanoparticles have been synthesised from *Solanum xanthocarpum* berry extract [10 nm (Ag)] (Amin et al. 2012), the roots extract of *Coleus forskohlii* [82.46 nm (Ag)] (Baskaran and Ratha bai 2013), potato extract (20 ± 1.2 nm (ZnO)) (Buazar et al. 2015), flower extract of *Hibiscus rosa-sinensis* [5–40 nm (Ag)] (Surya et al. 2016), *Dioscorea alata* tuber extract [10–25 nm (Ag)] (Pugazhendhi et al. 2016), the latex of *Thevetia peruviana* [10–30 nm (Ag)] (Rupiasih et al. 2013), the rind extract of *Citrullus lanatus* fruit [17.96 ± 0.16 nm (Ag)] (Ndikau et al. 2017), *Gum karaya* extract [1.5 nm (Pd), 5 nm (Ag), 12 nm (Pt), 42 nm (Au) and 180 nm (CuO)]

(Nguyen et al. 2018) to name a few. Plant-based synthesis is more rapid and possess greater stability in comparison to microbial synthesis and is also suitable for mass production (Iravani 2011).

Microbial synthesis of nanoparticles: bacterial and fungal sources

Bacterial synthesis Microbial synthesis involves reduction of target ion to element metal by the action of enzymes produced by cell activities (Li et al. 2011). Silver nanoparticles of spherical shape and size between 65 and 70 nm were produced using optimized culture of *Bacillus sp.* (Chelladurai et al. 2013). Optimization was carried out by Response Surface Methodology. Growth parameters such as pH, temperature and nitrogen source were varied to obtain increased culture production. Exopolysaccharide (EPS) extracted from the bacterial strain, *Leuconostoc lactis* acted as both reducing and stabilizing agent in the production of silver nanoparticles having average size of 35 nm (Saravanana et al. 2017). The synthesised silver nanoparticles exhibited excellent thermal property up to 437.1 °C. The coli form bacteria *E. coli* was also used to manufacture silver nanoparticles size in the range of 20–50 nm by making use of the culture filtrate (Kushwaha et al. 2015). Tetragonal crystalline SnO_2 nanoparticles (size 10 to 42 nm) were synthesised using Gram-negative bacteria *Erwinia herbicola* (Srivastava and Mukhopadhyay 2014). The reduction and stabilization of SnO_2 nanoparticles was executed by the bacterial protein and biomolecules. *Deinococcus radiodurans,* an extreme bacterium has been utilized for manufacture of gold nanoparticles. Spherical, triangular and irregular shaped nanoparticles were synthesised in the process having an average size of 43.75 nm and a polydispersity index of 0.23 (Li et al. 2016). Non-pathogenic bacteria *Pseudomonas fluorescens* was used for copper nanoparticle generation (Shantkriti and Rani 2014). The cell-free culture supernatant was used in the process which produced spherical and hexagonal shaped nanoparticles of average size 49 nm.

Fungal synthesis Fungal sources are also widely studied for fabrication of eco-friendly and sustainable nanoparticles. Both gold and silver nanoparticles were reported to have been synthesized from mycelial free filtrate of *Aspergillus terreus* having size 10–50 nm and 8–20 nm respectively (Balakumaran et al. 2016). The bioreduction potential of *Aspergillus terreus* to produce nanoparticles was attributed to NADH (nicotinamide adenine dinucleotide) and NADH-dependent reductase (Li et al. 2012). *Fusarium oxysporum* was also utilized to produce size-controlled silver nanoparticles (Husseiny et al. 2015) which is reported to have produced the largest number of different types of nanoparticles (Zielonka and Klimek-Ochab 2017). The yeast *Saccharomyces cerevisiae* model produced fairly monodispersed silver nanoparticles predominantly within 5–20 nm (Niknejad et al. 2015). Gold nanoparticles were produced from thermophilic filamentous fungal strains (Molnár et al. 2018). It was reported that the process took place in two steps, firstly Au^{3+} was reduced to Au^0 and secondly, the core of NPs was stabilized by capping agents which should be biopolymers greater than 3 kDa. Biomolecules secreted by the fungal strains which were less than 3 kDa only were capable of reducing Au^{3+} to Au^0 and synthesise gold nanoparticles.

Applications of nanoparticles

Nanotechnology has found applications in wide range of disciplines due to enhanced properties of materials in the nanoscale that differ from their bulk material (Ramrakhiani 2012). In recent years, research in nanotechnology has touched almost all fundamental disciplines mainly medicine (Nikalje 2015), agriculture (Kah 2015), automotive industry (Malani et al. 2016), electrical transformers (Contreras et al. 2017), food technology (Singh et al. 2017) and environmental remediation (Guerra et al. 2018) to name a few. With the scientific community constantly on the lookout for sustainable and biocompatible techniques for mitigation of environment problems, the elimination of toxic precursors and expensive as well as hazardous methodology has put green nanotechnology as the front runner for environmental application. The applications of green synthesised nanoparticles in environmental remediation, dye degradation and applications against water contaminating microorganisms have been briefly reviewed (Fig. 1).

Nanotechnology for antibacterial activity

Due to the excellent physiochemical nature and the antimicrobial potential of nanomaterials, they are widely used against various pathogenic microbes and in healthcare, crop protection, water treatment, food safety, and food preservation (Baranwal et al. 2018; Bajpai et al. 2018). Contamination of water by pathogenic bacteria and consequent spread of diseases like cholera, diarrhoea, gastrointestinal illness etc. has become a major world problem (Pandey et al. 2014). As per the Guidelines for drinking-water quality, World Health Organization 2017, some of the severe and life-threatening diseases like typhoid, cholera, infectious hepatitis etc. are caused by pathogens like *Escherichia coli, Salmonella Typhi, Shigella* spp. etc. transmitted through contaminated drinking-water. In this regard, nanotechnology offers a cost-effective and rapid solution for wastewater treatment by making use of the remarkable attributes of nanoparticles, such as high surface-to-volume ratio, photocatalytic and antimicrobial activity, tunable pore size and surface chemistry (Qu et al. 2013). The bactericidal property of

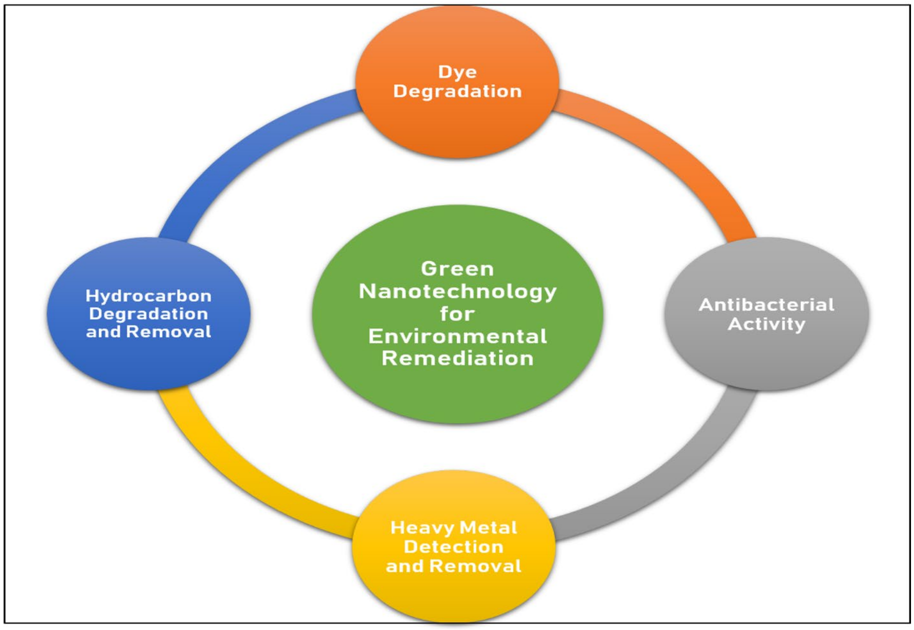

Fig. 1 Various applications of green nanotechnology in environmental remediation

silver nanoparticles synthesised using two filamentous fungi *Penciillium citreonigum Dierck* and *Scopulariopsis brumptii Salvanet* was established by testing against Gram positive and Gram negative bacterial strains (Moustafa 2017). Polyurethane foam incorporated with silver nanoparticles was used as a medium for inactivating pathogenic bacteria in contaminated waters. Spherical silver nanoparticles (15 nm to 20 nm) produced using ripe *Carica papaya* peel extract as the reducing agent exhibited well-defined inhibition zones against pathogenic bacteria *Escherichia coli* (Gram negative) and *Staphylococcus aureus* (Gram positive) (Balavijayalakshmi and Ramalakshmi 2017). The zone of inhibition was found to be a remarkable 0.75 cm (75 mm) for *E. coli* and 0.65 cm (65 mm) for *S. aureus* for 100 µl of silver nanoparticles. Silver nanoparticles fabricated from olive leaf extracts resisted bacterial growth against drug resistant isolates of "*Staphylococcus aureus*, *Pseudomonas aeruginosa* and *Escherichia coli*" (Khalil et al. 2014a, b). Silver nanoparticles have shown remarkable inhibiting activity against a number of different bacteria such as "*Escherichia coli, Pseudomonas aeruginosa, Klebsiella pneumonia, Shigella flexneri and Bacillus subtilis"* (Bagherzade et al. 2017).

Apart from silver which is a known antibacterial agent, other metallic and metal oxide nanoparticles have also shown significant inhibiting activity against bacteria. Biosynthesised gold nanoparticles showed antibacterial activity against "*Escherichia coli, Klebsiella pneumoniae*, MRSA, *Staphylococcus aureus* and *Pseudomonas aeruginosa"* (Abdel-Raouf et al. 2017). Cubical iron oxide nanoparticles of size 30 mm to 100 nm synthesised from *Lagenaria siceraria* leaves extract were assessed for antibacterial activity and showed 10 mm zone of inhibition for *Escherichia coli* and 8 mm for *Staphylococcus aureus* (Kanagasubbulakshmi and Kadirvelu 2017). At low concentration, zinc oxide nanoparticles produced by *Catharanthus roseus* leaf extract demonstrated bacteriostatic property whereas at high concentration they became bactericidal (Gupta et al. 2018).

Applications of green nanoparticles in environmental remediation

As the world is heading towards rapid development through new technologies and innovations, the exploitation of our natural resources has also seen exponential rise raising valid concerns. Over the past years, researchers have shown keen interest in the utilization of nanotechnology in environmental remediation. The enhanced affinity of nanoparticles towards contaminants, their increased reactivity and ease of disposal augments their performance in environmental remediation (Yunus et al. 2012). From the available literature, it is evident that green synthesis of nanoparticles serves two purposes. One, it provides a clean, non-toxic, environment friendly method of production of nanoparticles by eliminating toxic precursors and toxic by-products and two, it acts as an effective and sustainable technique for environmental remediation.

Nanotechnology for dye degradation

Effluents from the textile industry pose a serious health and environmental concern because of the toxicity and carcinogenicity of the dyes released along with the industrial wastewater (Ratna Padhi 2012). The conventional methods of treatment are cost-intensive, complicated procedures and generate significant sludge content causing secondary pollution (Anjaneyulu et al. 2005; Saratale et al. 2011). Treatment of dyes using biogenic nanoparticles presents a more viable, cost-effective and environment-friendly alternative by eliminating complicated machinations and procedural conditions (Jyoti and Singh 2016).

Singh et al. (2018) reported the use of *Piper betle* leaves extract for the production of Tin Oxide (SnO_2) nanoparticles. Biosynthesised SnO_2 NPs (average size 8.4 nm) underwent photocatalytic reaction under direct sunlight to degrade industrial dye Reactive Yellow 186 (RY186) with an efficiency of 92.17%. SnO_2 Quantum Dots (QDs) synthesized with the help of biomolecules present in sugar cane juice bore size ~ 2.5–4.5 nm with spherical shape and crystalline form of tetragonal structure (Bhattacharjee and Ahmaruzzaman 2015). The SnO_2 QDs were successfully tested under direct sunlight for photocatalytic potential against Rose Bengal (RB) and Methylene blue (MB) dye degradation. The optical absorption spectra of RB and MB solutions were analysed to ascertain the break-down of the two dyes. The RB dye solution became colourless within 180 min of addition of biogenic SnO_2 QDs and the absorbance band at 540 nm disappeared. Likewise, the absorption band of MB at 663 nm disappeared within 240 min and the colour faded away. The ascorbic acid synthesised SnO_2 nanoparticles was reused up to four times for Methylene blue dye degradation effectively without any observable variation in percentage of degradation after recycling (Tammina et al. 2018).

Photocatalytic activity of spherical silver nanoparticles (79 to 96 nm) synthesized under different pH from *Morinda tinctoria* leaf extract was investigated for break-down of Methylene Blue dye under sunlight (Vanaja et al. 2014). There was no nanoparticle production detected in the acidic medium but the size and quantity of silver nanoparticles generated in the alkaline medium was highly pH dependent. Gradual decrease of the main absorption peak of the dye at 660 nm was observed on application of silver nanoparticles in sunlight with the increase in exposure time. Finally, the process completed at 72 h when the dye solution turned colourless with degradation efficiency calculated at 95.3%. Silver nanoparticles developed using fruit extract of *Gmelina arborea*, also showed excellent catalytic properties of AgNPs by completing the catalytic degradation reaction of methylene blue dye within 10 min (Saha et al. 2017).

Several other metallic and metal oxide nanoparticles have also been reported in literature to exhibit effective catalytic properties towards degradation of harmful dyes. Gold nanoparticles fabricated using *Alpinia nigra* leaves extract catalysed the break-down of the Methyl Orange and Rhodamine B dyes in presence of sunlight with percentage degradation of 83.25% and 87.64% after 120 min, respectively (Baruah et al. 2018). Silver and gold nanoparticles produced from *Stemona tuberosa Lour* plant extract behaved as excellent catalysts in the complete degradation of 4-nitrophenol, methylene blue, methyl orange and methyl red in presence of sodium borohydride (NaBH4) (Bonigala et al. 2018). Zinc oxide (ZnO) nanoparticles synthesised from *Artocarpus heterophyllus* leaf extract brought about effective photocatalysis in the degradation of Rose Bengal dye with efficiency greater than 80% at 0.24 g/L within one hour (Vidya et al. 2016) and that of Congo red dye with efficiency greater than 90% at 0.24 g/L of ZnO nanoparticles in one hour (Vidya et al. 2017). The breakdown of Congo red dye was carried out at pH 9 under UV light at room temperature. Iron oxide nanoparticles of spherical morphology with dimension between 5.68 and 30.29 nm were produced using *Teucrium polium* leaf extract (Kouhbanani et al. 2019). The H_2O_2 catalysed by iron oxide nanoparticles efficiently decolorized Methyl Orange dye by 73.6% within 6 h.

Nanotechnology for heavy metal detection and removal

Heavy metal contamination of water sources emanates mainly from industrial effluents which contain of toxic metal ions such as copper, lead, cadmium, arsenic and mercury (Gunatilake 2015). Heavy metals are non-biodegradable and tend to bioaccumulate in bodies of living beings and their innate toxicity deals great damage to human health (Verma and Dwivedi 2013). Recent literature confirms that nanoparticles have shown promising results in removal of heavy metals. Silver nanoparticles prepared using *Ficus benjamina* leaves extract and $AgNO_3$ were effectively used for removal of Cd (II) ions (Al-Qahtani 2017). The removal of cadmium ion was dependent on “adsorbent dose, heavy metal concentration, pH, agitation speed and contact time”. Proanthocyanidin-functionalized gold nanoparticles showed high efficiency in the removal of methylene blue dye and heavy metal ions like Ni^{2+}, Cu^{2+}, Cd^{2+} and Pb^{2+} (Biao et al. 2018). Toxic heavy metal lead Pb^{2+} was removed by using Fe_3O_4 magnetic nanorods (MNRs) which were anchored on dimercaptosuccinic acid (DMSA). Fe_3O_4 MNRs were biosynthesised from *Punica granatum* rind extract (Venkateswarlu et al. 2014). Electrostatic force of attraction which existed between Pb^{2+} ions and DMSA anchored Fe_3O_4 MNRs facilitated the adsorption process at different pH. Adsorption of Pb^{2+} was highest (46.18 mg/g) at pH of 5 for a dosage of 0.1 g/L and temperature 300 K. The removal could be further speeded up by using an external magnet. Cadmium sulphide (CdS) nanoparticles were prepared using *Spirulina platensis* (blue-green algae) (Mandal et al. 2016). Interestingly, the production was carried out without using any sulphur precursor. During the synthesis which was carried out in situ in the algae, toxic Cd^{2+} ion was converted to less toxic CdS nanoparticles. The biosynthesised CdS nanoparticles also exhibited photocatalytic efficiency in breakdown of malachite green dye. In another study, Zinc oxide (ZnO) nanoparticles fabricated from leaf extract of *Emblica officinalis* with particle size of 16 nm and rod like morphology were utilized for the removal of arsenic As^{3+} ions which were embedded in activated silica (Gnanasangeetha and Umamageshwari 2017). Maximum removal of As^{3+} ions that was achieved was 96.7% which corresponded to concentration of 0.002 mg/L using absorbent dosage of 2.5 g at pH of 5 for time 60 min and agitated at 300 rpm. Mercury (Hg) was removed by silver nanoparticles synthesized using *Aloe vera* extracts made with water and ethanol (Vélez et al. 2018). For aqueous extract, the sizes of the nanoparticles synthesized were between 3 and 14 nm and for ethanolic extract between 2 and 7 nm. Concentration of nanoparticles as low as 20% V/V for both extracts yielded removal of more than 95% mercury.

Hybrid nanomaterials and multicomponent nanoparticles have also been studied for removal of heavy materials. Inorganic–organic hybrids are advantageous as that they can integrate the often dissimilar properties of organic and inorganic components into a single material and create multifunctional materials (Kickelbick 2007). Such a hybrid was created by encapsulating iron oxide nanoparticles into chitosan beads having magnetic properties (Martínez-Cabanas et al. 2016). The iron oxide nanoparticles were synthesised from *Eucalyptus globulus* plant extract. Column experiments showed near total removal of arsenic using iron oxide nanoparticle beads showing effective absorbance at natural pH. In another study, mortiño berry (*Vaccinium floribundum Kunth*) extract was allowed to react with ferric chloride ($FeCl_3$) and sodium sulphate (Na_2SO_4) to produce multicomponent nanoparticles (MCNPs) (Abril et al. 2018). The MCNPs produced by the reaction of berry extract, 0.5 M $FeCl_3{\cdot}6H_2O$ and 0.035 M Na_2SO_4 in 0.5:10:10 (V/V/V) ratio exhibited efficiency of greater than 99% in the removal of copper and zinc from aqueous medium for pH above 6. The biosynthesised MCNPs were also used to treat heavy metal contaminated soils and immobilization tests resulted in more than 95% efficiency for tested metals.

Colorimetric detection of heavy metal ions was made possible by silver and gold nanoparticles produced using the amino acid, *L-tyrosine* under direct sunlight (Annadhasan et al. 2014). Silver nanoparticles detected Hg^{2+} and Mn^{2+} ions in aqueous medium with concentrations as low as 16 nM under optimized conditions. However, gold nanoparticles showed sensitivity towards Hg^{2+} and Pb^{2+} ions by detecting their presence at low concentrations of 53 and 16 nM of respectively.

Nanotechnology for hydrocarbon degradation and removal

Hydrocarbon pollution is one of the most severe threats to the environment because of the toxicity rising from carcinogenic and hazardous components (Das and Chandran 2011). Petroleum which is a complex mixture of different hydrocarbon compounds is a common source of hydrocarbon pollution (Shukla and Cameotra 2012). Nanotechnology has emerged to be an effective method for remediation of hydrocarbon contaminants as it has the potential to reduce the clean-up costs and time of large-scale contaminated sites and minimize pollutant concentrations in situ (Nnaji 2017). In a study, *Coriandrum sativum* leaf extract was used to reduce zinc acetate dehydrate to synthesise zinc oxide nanoparticles. Photocatalysis using the synthesised zinc oxide nanoparticles was then carried out in a batch photocatalytic reactor for the remediation of anthracene, a toxic solid polycyclic aromatic hydrocarbon (Hassan et al. 2015). The optimal results were obtained for a nanocatalyst dose of 1000 µg/L at a pH of 7 and exposure to UV radiation for 240 min. This led to a 96% degradation of anthracene. The remediation of the poly aromatic hydrocarbons (PAHs), viz. phenanthrene, anthracene and pyrene via silver nanoparticles was also studied by Abbasi et al. (2014). The synthesis was carried out by both green and wet chemical method using garlic (*Allium sativum)* extract. Concentration of 0.01 mg/L of each of phenanthrene, anthracene, and pyrene was used to make a synthetic solution. 1 mg/kg of both the synthesized nanoparticles were used as adsorbents for the prepared solution. The removal efficiency was highest for phenanthrene, followed by pyrene and anthracene with optimal efficiency recorded above 85%. Interestingly, it was further noted that silver nanoparticles synthesised through green method proved to be better absorbents of PAHs than their wet method synthesised counterparts. In another study, ZnO/SiO_2 nanoparticles synthesised from powder extract of *Butea monosperma* (Palash) leaves were used as nanocatalyst for the remediation petroleum refinery effluent (Bharati and Suresh 2017). The aim of the study was to achieve degradation of acenaphthylene, a polycyclic aromatic hydrocarbon and reduction of chemical oxygen demand (COD) in the refinery effluent. 1 g/L of ZnO/SiO_2 nanoparticles used as photocatalyst under UV-light at 30 °C for 4 h gave the optimal removal percentage at 75% for COD (mg/L) and 73% for acenaphthylene. Zero valent iron nanoparticles were synthesized using green mango peel extracts whose role as a catalyst in petroleum hydrocarbon remediation of soil polluted by oil sludge was assessed (Desalegn et al. 2018). Oxidation of total petroleum hydrocarbon using persulphate which was catalysed by iron nanoparticles indicated more than 90% degradation over a week. Further, biosynthesised zero valent iron nanoparticles were more efficient than the chemically synthesized ones in terms of TPH removal efficiency, cost effectiveness and environmental risks. In another study pertaining to hydrocarbon remediation, iron nanoparticles of size 5–10 nm and spherical shape were synthesised using the extract of mortiño berry (*Vaccinium floribundum*) (Murgueitio et al. 2018). The biosynthesised iron nanoparticles were examined for remediation potential against total petroleum hydrocarbon (TPH) present in contaminated soil and water. The iron nanoparticles successfully removed 88.24% TPH from water sample and 81.90% from soil sample after 12 min and 32 h of treatment respectively.

Conclusion and future perspectives

The ever growing challenge to engineer benign techniques for countering and mitigating environmental problems emanating from anthropogenic activities has created an imperative need for sustainable alternatives leading researchers into exploring the domain of green nanotechnology. Biological resources like leaves, flowers, fruits, roots, tubers, latex of plants, bacteria, fungi, yeast etc. have been successfully employed for generation of stable nanoparticles via the green method. This green synthesis method, apart from being simple to implement, eco-friendly and cost-effective, also provides a sustainable mode of mass production. The enhanced inherent qualities of materials in the nanoscale have already intrigued researchers and thus, have found diverse applications. This review discusses the various biogenic precursors that can be effectively utilised for green synthesis of nanoparticles and thereby showcasing the potentiality of such biogenic nanoparticles in the field of environmental remediation. The excellent catalytic property of nanoparticles have shown immense potential in the degradation of major environmental contaminants with varying degree of success. Further study should be made to determine the optimum conditions for biosynthesis of nanoparticles as well as for environmental application of such nanoparticles to obtain uniform success rate. It has also been observed that the remediation of hydrocarbon contaminants using green nanoparticles has been comparatively under-explored in spite of promising results. The current trend demands broadening of the domain of this research on a more wholesale level by investing time, resources and manpower to enable mainstream implementation of this technology in the prospective future. Thorough research should be conducted to study the toxicity of nanoparticles released into the environment and also evaluate their fate and transport study. On the whole, as the size of particles gets smaller, the scope to explore newer possibilities increases manifold.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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