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Review Article

Implementations of Green synthesized Nanoparticles from Biomedical to Construction Industry: An approach of sustainability

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Abstract

The technology-dependent world always finds innovations for the betterment of our living ways to add extra steps of developing new lifestyles and products in the public that fulfil unaddressed needs or solve problems that were not in the past. Starting from 1959 nanoparticles -based techniques have become an integral domain of our life and recent inclusions of green synthesized nanomaterials initiate a significant impact in creating an eco-friendly environment that will be helpful to develop a sustainable growth on which the economy and society depend. In this article, we emphasize the possible implementations of various green synthesized nanoparticles in each and every possible sector of life along with their advantages and limitations. Our review work may be useful to the researchers involved in this field and also to the people to concern about the benefits and the risk of green synthesized nanoparticles.

Keywords: Green synthesized nanoparticles, ecofriendly, nanotechnology, nanofertilizers, cosmeceuticals, pollution control, biomedical applications, and sustainable development

Background

Nanoparticles (NPs) are omnipresent in nature. From the very beginning of the earth's history, NPs were present naturally in air, water, and soil. Many bio-molecules like proteins, nucleic acids, viruses are also present in nanoforms and they are often released in the environment through the dispersion of viruses, nucleoprotein exudation, etc. [1]. Records show that NPs derived from natural combustion processes deposited in 10,000 years old glacial ice cores via atmospheric deposition [2].

NPs are particles of small size (< 100nm) and large surface to volume ratio, because of which they exhibit some unique physiochemical properties that are different from their bulk form [3, 4]. Most of these changes are related to the appearance of quantum effects as the size decreases [5]. However, physical properties such as shape, melting point, viscosity, conductivity, electrical behavior, etc. are also size-dependent [6, 7]. Engineered NPs (ENPs) are used extensively for various purposes as these new materials are potentially very beneficial to human endeavours both in physical and biological systems [8]. However, some of them also have toxic effects. But their applications could not be prevented, as prior to that scientists have already prepared ENPs in a green route called green-synthesized NPs (GSNPs).

The advent of nanotechnology has provided a wealth of GSNPs that can be utilized in different fields [9] especially in different ways to tackle bio-related issues, a possible area of wide ramification which was being neglected due to lack of relevant technology and understanding.

Carbon nanotubes (CNTs) and their derivatives are used for sorption of metals such as copper, nickel, cadmium, lead, silver, zinc, americium and rare earth metals, in electronics and computers, in plastics, catalysts, battery, fuel cell electrodes, supercapacitors, water purification systems, orthopaedic implants, conductive coatings, adhesives, composites, sensors, components in electronics, aircraft, aerospace, and automotive industries, sporting goods among others [10, 11].

Fullerenes are used in the sorption of organic compounds (e.g. naphthalene) and for the removal of organometallic compounds and in cosmetics. Metal oxide NPs like TiO_2 is used in cosmetics, skincare products, sunscreen lotions, in solar cells, paints and coatings [12, 13] ZnO NPs are also used in skincare products, solar cell, bottle coatings [14, 15]. Another metal oxide NP, CeO_2 is used as combustion catalyst in diesel fuels to improve emission-quality, in gas sensors, solar cells, oxygen pumps, in metallurgical and glass/ceramic applications, in semiconductor devices, in photovoltaic cells, photonics and telecommunications [16, 17].

Zero-valent iron (or ion?) NPs are used in the remediation of water, sediments, and soils to remove nitrates and organic contaminants, in detoxification of organochlorine pesticides, and in polychlorinated biphenyls [18, 19]. Silver NPs are used in air filters, toothpaste, babyproducts, vacuum cleaners, and washing machines. Colloidal elemental gold is used in flexible conducting inks or films [20, 21].

Nowadays different NPs are used in a variety of biological systems like fluorescent biological labels [22], gene and drug delivery [23, 24], detection of pathogens [25], detection of proteins [26 - 28], probing of DNA structure, and in tissue engineering [29- 31]. CNTs are widely used in biomedical systems for early detection of the cancerous tumor. TiO_2 is also used in bioremediation and for the removal of various organics (phenol, p nitrophenol, salicylic acid) [26]. ZnO NPs are used in skincare products. CeO_2 quantum dots (QDs) are used in medical imaging and targeted therapeutics. Zero-valent iron (or ion?) is used in bioremediation for the decomposition of molinate (a carbothionate herbicide). Silver NPs are used in wound dressing and colloidal elemental gold NPs are used as a vector in tumour therapy [23]. Polymers are used in the manufacture of macromolecules, in drug delivery, and DNA chips. It is also used as a powerful anticancer drug. Polymers are also used as DNA transferring agents and therapeutic agents for prion diseases [30]. Magnetic GSNPs are now used in cancer treatment via hyperthermia (tumour destruction by heating) [32]. These GSNPs also help in the separation and purification of biological molecules and cells [33].

Explorations of GSNPs in the above said different fields enrich our life by easy handling and make us fulfil our dream to furnish a sustainable nanotechnology-based world. Although GSNPs have many advantages over ENPs, they also have some limitations that we must consider. In our article, we have also summarized the possible pros and cons of GSNPs along with their vast applications in different sectors that have opened an exciting future of scientific convergence and technological integration with the promise of broad societal implications towards sustainable development.

Sources of GSNPs:

Many ways have been developed so far to fabricate NPs in green methods to avoid the chemical and physical methods as they are expensive, laborious, and show toxicity to some extent. The biological method of NPs synthesis follows the bottom-up fabrication where synthesis occurs with the help of reducing stabilizing agent. Depending on the source of biological materials, GSNPs can be categorized broadly into two categories [**Figure 1**].

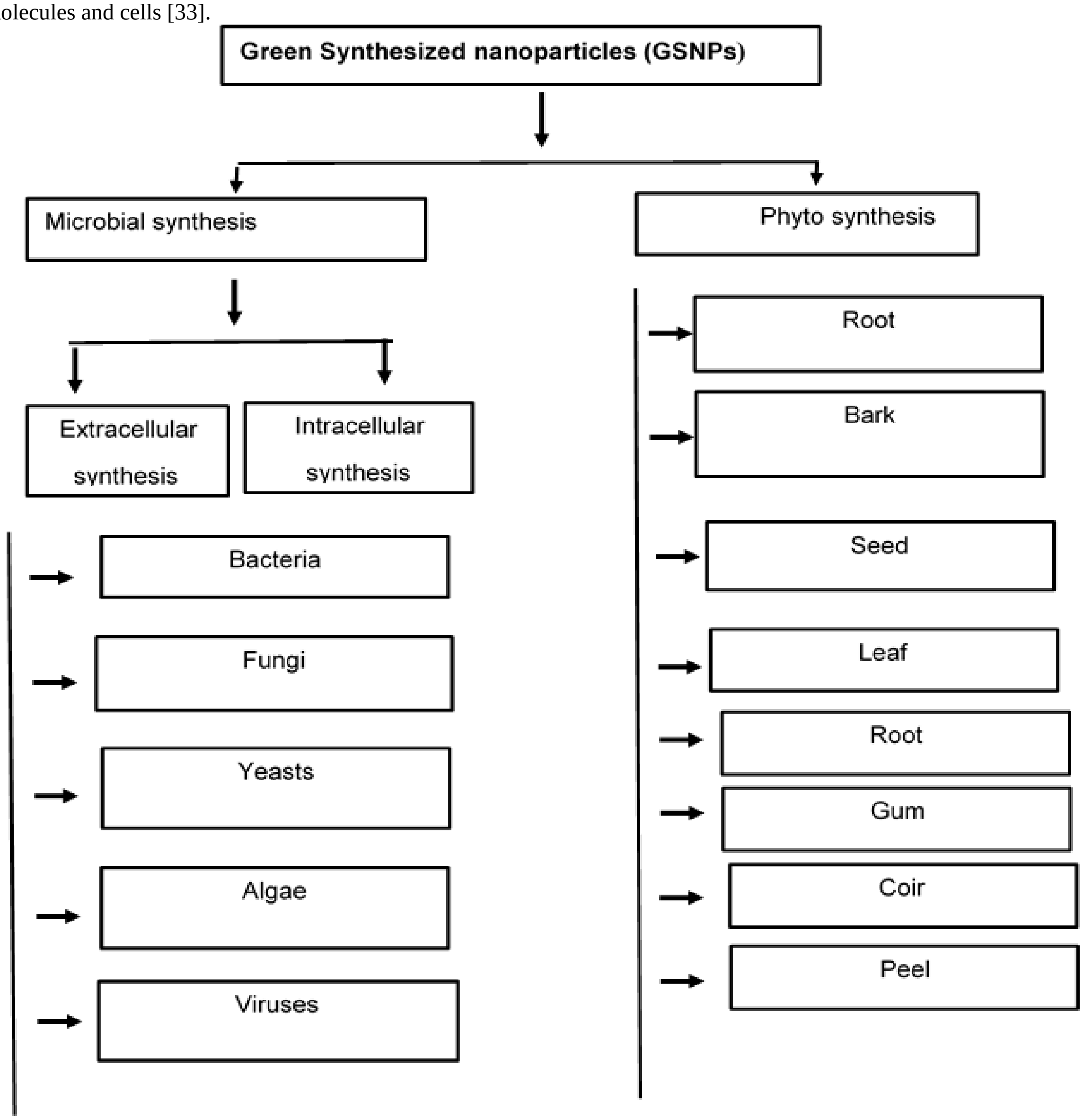

Figure 1. Schematic representation of different synthesis pathways of GSNPs

A] Microbial synthesis: In this type, prokaryotic bacteria, fungi, as well as eukaryotic algae and viruses, are used to generate GSNPs. Many new inventions arise day to day of which we have mentioned here a few of them.

i) Bacterial synthesis: Ag and Au NPs can be synthesized from *Pseudomonas stutzeri* and *Proteus mirabialis* respectively [34, 35]. TiO_2 salt combined Bacillus sp based culture synthesize TiO_2 NPs [36, 37] and CdS NPs can be generated from E. coli [38]. PbS and ZnO NPs with spherical particle size are synthesized from some bacterial strains through controlled incubation [39, 40].

ii) Fungal synthesis: Some species of *Colletrotricum sp*, *Fusarium sp*, and *Volvariella volvasea* can reduce gold salt to produce spherical-shaped Au NPs [41-43] Aspergillus can produde TiO_2 and Verticillium along with *Phaenerochaete chrysosporium* can be used to generate AgNPs during their incubation with the corresponding metallic salts [44-46].

iii) Algal synthesis: Many phaeophycean and chlorophycean algae are being used recently in NPs production through the green route. Production of nano gold can be made from Chlorella vulgaris and many other green and brown algae. The unicellular green algae, *Chlorella vulgaris* can reduce Au from aurochloric acid as the algae have a strong binding affinity in its dried form to the salt solution [47].

iv)Yeast mediated synthesis: Hexagonal Ag and Cd NPs can be synthesized from some species of Yeast, *Schizosacchromyces pombe, and* MKY3 [48, 49]. Ag and Au NPs are synthesized by using culture supernatant of *Saccharomyces cerevisae* and *Candida guilliermondii* respectively [50]. Yeast cells mediated synthesis of $Fe3O_4$ and Sb_2O_3 have also been recorded [51-53].

v) Virus mediated synthesis: Researchers have already proved that CdS and ZnS can be synthesized by using M 13 bacteriophage [54] and the popular Tobacco mosaic Virus i.e. TMV can successfully generate SiO_2, CDS, Fe_2O_3 and PbS in both extra and intracellular means of synthesis [55].

B] Phytosynthesis:

Green mediated synthesis of NPs is broadly based on the higher plant-mediated synthesis of different metal, metal oxide, nobel metal, and other types of NPs. Nowadays extract from different plant part like root, stem, bark, leaf, choir, gum, flower, fruit, leachates from dry seed, etc are used frequently to synthesize rapid, homogenous, cost-effective means of NP generation. First NPs generation was started by using Alfaalfa sprouts [56] and after that, there are lots of plant species from different plant families that have been enlisted their names in phytogenic NPs synthesis [57-68]. Generally, the active component present in the extracted plant parts acts as a reducing agent and produces GSNPs whenever react with a different metallic salt. However, many other factors like temperature, the concentration of both salt and plant extract, nature of the active component in plant extract, pH, etc are responsible for the size and shape of the GSNPs.

Applications:

The beneficial role of GSNPs has wide applications in various aspects of life including the biomedical industry, agricultural sector, an industry of alternate energy source, pollution control, environmental remediation, food, and cosmetics industry and many are under research ground [**Figure 2**]. Following is a summary of the involvement of GSNPs

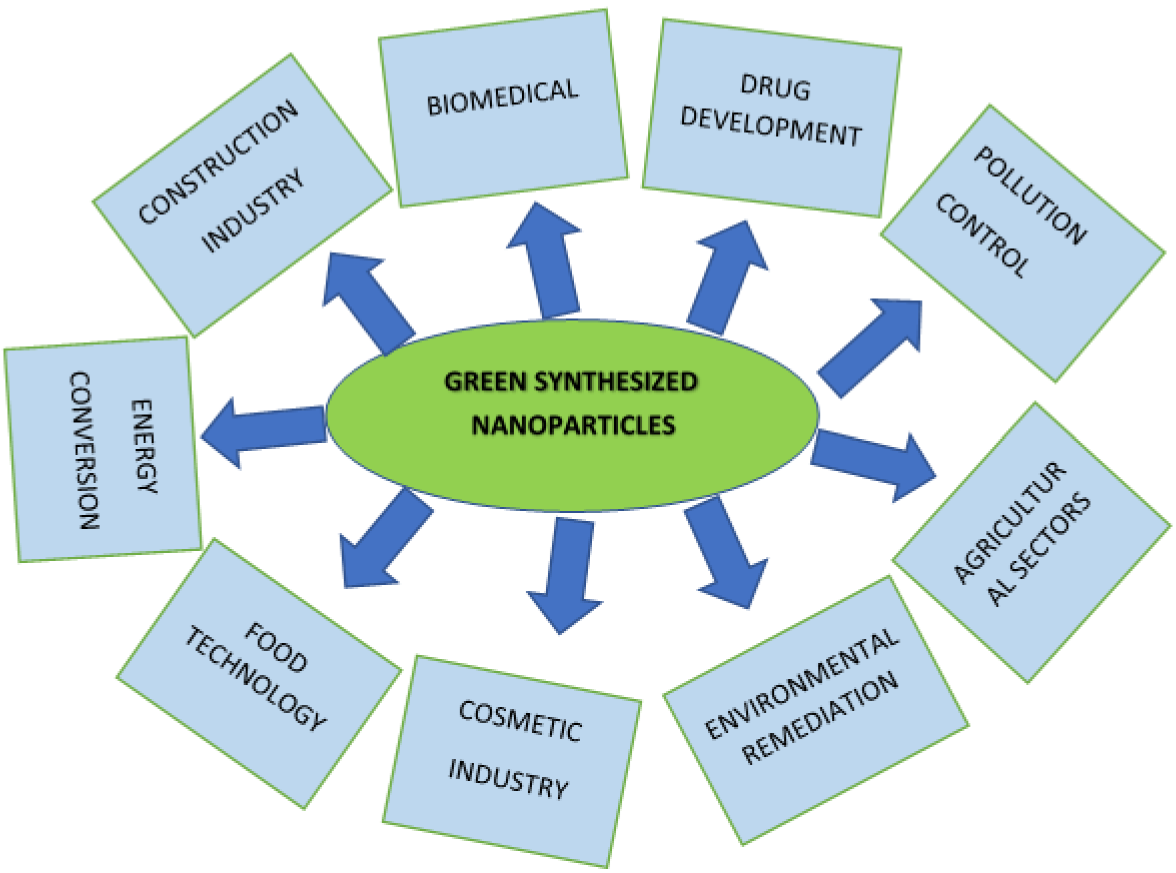

Figure 2. Diagrammatic representation of green synthesized nanoparticles in different aspects

A] Biomedical / Therapeutic

a) Wound dressing material

Treating wounds in any living being always concerns about rapid healing effects and without any side effects. Many GSNPs have successfully overcome the problem of infection in wound healing. Silver NPs for wound healing application were developed using *Indigofera asphlathoides* without adding any harmful toxic chemicals as a wound healer.

Nanofibers are the porous structure that makes them desirable for wound dressing material and wound healer & has a high success rate as due to their oxygen permeability, maintaining moisture at the desired level simultaneously inhibits microbial invasion [69]. Incorporation of wound healing drugs in a narrow structure of cellulose acetate nanofiber shows an increase in collagen synthesis which is relevant to wound healing and cellulose acetate nanofibers are biocompatible in nature and enhances the healing process [70, 71].

Nanostructure wound dressing material which is made up of cellulose acetate is prepared by co-electrospinning of biopolymers with polyester urethane and gelatin [72-74].

These special materials show air permeability, antimicrobial activity, and accelerates the healing process rapidly, and help the skin cell to generate faster and treat the injured area.

Asiaticocide, a phytochemical obtained from *Centella asiatica* was loaded on cellulose acetate nanofibers which helps to heals the wound at the earliest stage of injury because of its antioxidant activity [75].

AgNPs synthesized from *Catharanthus roseus* leaf extract when tested on mice model showed a controlled growth of bacteria and fungi in the wounded area proved to show antimicrobial activity in the wounded region [76].

TiO_2 nanoparticle from *Moringa oleifera* leaves shows their efficacy in wound healing activity similarly copper oxide NPs from *Ficus religiosa* leaf extract proved to act as an excellent healer and because it increases the formation of fibroblast and collagen fiber in the affected region [77-79].

b) Bio-imaging:

Water dispersible fluorescence carbon Quantum dots were synthesized from *Saccharum officinarun* juice act excellent as a fluorescent probe for cell imaging in microorganisms [80]. Water-soluble carbon Nano- onions are fluorescent reagents used for imaging live species like *Drosophila melanogaster*. Carbon Nano -onion synthesized from wood waste (a biological sample) contributed to the discovery of oral ingested Probe which is completely non-toxic in nature. Results were detected through optical fluorescence microscopy. They were successfully exhibited images of all stages of development of a live fruit fly [81].

c) Bio-sensors:

GSNPs have low cytotoxicity and are very specific with respect to the substrate and chemical interactions. The surface modifications are quite flexible which makes them very potent in detecting any chemical or biological agent in trace amounts and they can act accurately as biosensors or detectors. The advantages of using bio-sensors are due to its cost-effectiveness and eco-friendliness. Mancozeb (MCZ) are well known Agro fungicide and pesticides applied in the crop field but has several side effects. Silver NPs synthesized from leaf extracts of many indigenous Indian herbal plants like Aloe vera, guava, neem, and mint can easily identify or sense this agro fungicide MCZ in food material if present at different concentrations. Sensing of this chemical is proved due to Blueshift in the surface Plasmon resonance peak of silver nanoparticle in presence of MCZ chemical. The SPR peak in the silver nanoparticle arises due to the resultant electric field at the nanoparticle surface which induces variation in the amplitude of current. Observation during the experiment was analyzed by using spectrophotometer [82].

Another experimental data that successfully proved the efficiency of green synthesized nanoparticle as biosensors *Ogataea polymorpha* yeast having extracellular metabolites efficiently act as a reducing agent in synthesizing metallic NPs. These are used in the construction of amperometric biosensors. Most successful approach was that of Palladium based nanoparticle, which is applied in the construction of laccase enzyme and alcohol oxidase based amperometric biosensor [83].

d) Drug delivery:

Gliadin Protein found in cereal are used as GSNPs which act as a carrier for oral administration of different drugs like lipophilic and anticancer drug [84].

e) Hyperthermia:

Hyperthermia has been in practice since the last decades, when they practically proved to help other radiation and chemotherapy in killing immortal cancer cells by maintaining tissue temperature around 42-45°C [85].

Thermal stress was created due to hyperthermia which further makes the tumor cell radiosensitive and makes them more responsive for radio and chemotherapy [86].

Metastatic squamous cancer cells showed, a very prompt action and induce apoptosis but unfortunately maintaining and managing precise temperature nearby a tumour tissue or in the Cancer cell is very challenging for the researchers. As a result of which, normal cells also got exposed with hyperthermia. Few examples of side effects of hyperthermia are like cardiac arrest, gastrointestinal diseases, etc [87]. *Theobroma cacao*, commonly known as the cocoa extract is a biological source where anisotropic gold nanoparticle was synthesized through an aqueous route Cancer cell death induced by this gold nanoparticle in carcinoma a431 cell line was observed and proved to be suitable for photothermal therapy [88]

f) Photoablation therapy:

Currently, nanoparticle-mediated target specificity is very popular which helps in solving the problem of local hyperthermia. GSNPs have potentiality in photothermal therapy (PTT).

Hyperthermia was induced by magnetic NPs on exposure to an alternating magnetic field. Brown seaweed (*Sargassum muticum*) was reported in synthesizing Fe_3O_4 NPs which proved to have superparamagnetic properties and are capable to use for hyperthermia in an alternating magnetic field [89].

Disadvantages of applying alternate magnetic fields are not restricted to tumor but whole-body exposure happens during the therapy. PTT is more target-specific than hyperthermia caused by magnetic field alteration [90].

PTT induces cellular apoptosis and is very successful in killing target specific cancer cells. The advantage of this recently developed therapy is that the light energy which is an external stimulus can be focused on any specific region and also the amount of light can be controlled [91]. PTT induces and increases the local temperature inside or nearby tumour cells.

Ferromagnetic GSNPs like iron oxide, superparamagnetic iron oxide NPs, single-wall carbon nanotube, and multiwall carbon nanotube have shown higher success rates when used for hyperthermic therapy [92].

Gold NPs and gold nanorods have shown thermal mediated induction of cell apoptosis in many experiments. The biocompatibility of this type of NPs also boosts up their chances to work for thermal ablation [93, 94].

B] Drug development

a) Antibiotic drug

One of the best implementations of GSNPs in recent arena is to produce antibiotic drugs. Uncontrolled use of antibiotics causes drug resistance in microbes. Bio-based, eco-friendly copper NPs are a solution to this problem. There is evidence that copper NPs synthesized from green tea (*Camellia sinensis*) and beta cyclodextrin, where polyphenols are present in the plant extract, acted as a reducing agent. These NPs were screened against many Gram positive and Gram-Negative bacteria and they also showed a synergistic activity with amphicin, amoxicillin gentamicin ciprofloxacin antibiotics when used against pathogenic microbes. So green synthesized copper NPs can be used in food packaging material to stop the growth of food pathogenic organism [95, 96]. Platinum NPs and cobalt NPs were also synthesized using aqueous and methanolic extract of *Morus indica* leaves and stem and these GSNPs showed antibacterial properties against *S. aureus, E coli, P. aeruginosa and E. facealis* [97, 98].

Copper oxide and gold NPs synthesized via green route are also very efficient against gram positive and negative organism [99]. Cu NPs derived from fungal source showed a antimicrobial property against many pathogenic strains like Gram-negative *Escherichia coli* ATCC 25922 and *Klebsiella pneumonia* ATCC 13883 and Gram-positive *Micrococcus luteus* ATCC 10240, *Staphylococcus aureus* ATCC 25923 and *Bacillus subtilis* ATCC 6633 [100, 101].

Zinc oxide NPs developed by using leaf extract of very commonly known plant *Hibiscus subdariffa* are proved to have antibacterial activity against *Staphylococcus aureus* and *E. coli*.

Iron oxide NPs produced by using leaf extract *Dodonaea viscos*a was studied for their antimicrobial activity against different human pathogenic strains [102].

Tridax procumbens, a weed that was used for the production of iron oxide NPs, showed their ability of inhibiting the growth of fungal pathogens like, *S. rolfsii* and *F. oxysporum* [103].

b) Antifungal:

Ocimum santrum mediated synthesis of Ag NPs has strong antifungal activity against some species of Candida, Aspergillus, Saccharomyces etc. that cause different fungal infections in human [104]. Nosocomial infection caused by Candida sp. with 40% mortality rate can be controlled by Ag NPs doped drugs [105-107].

c) Anti- viral:

It has been proved that Ag NPs also have the capability to prevent infection caused by human viral pathogen. Ag NPs act as anti-HIV-1 agent and can prevent after- surgery infections [108]. Actually, AgNPs hinder the binding affinity of viruses to the host cell receptors [109, 110].

d) Antidiabetic:

Potential of Copper NPs as an antidiabetic was analysed through alpha-glucosidase assay. Alpha glucosidase enzyme inhibitor activity was found because of the presence of copper oxide nanoparticle which further proves that it has antidiabetic property.

Zinc oxide nanoparticle from leaf extract of *Hibiscus subdariffa* successfully proved that it helps to induce the T helper Cell 1 and 2 and also helps to express other insulin receptor genes in the pancreas which are associated with diabetes in diabetic mice model. Streptozotocin induced diabetes and genetic expression was proved by ELISA and RT-PCR results [111].

Silver and iron NPs were synthesized using this formulation which has antioxidant properties which was proved by hydrogen peroxide scavenging assay and nitric oxide scavenging activity. Iron nanoparticle's alpha amylase inhibition activity was tested and evidenced to have antidiabetic activity. Iron nanoparticle was therefore proposed to be used for post prandial glucose control [112]

e) Anti-inflammatory:

Since many years NPs have been shown as an anti-inflammatory agent due to their small size which help them to invade in the local inflammatory area very smoothly and act accordingly. Phyto-reduced ZnO NPs from *Trianthema portulacastrum* Linn. leaf and *Heriteira fomes* reported to be anti-inflammatory agent because they successfully inhibit albumin denaturation, protein denaturation and also stops protein's as enzymic activity which finally stops the inflammation. Zinc oxide nanoparticle also produces Myeloperoxidase level and decrease neutrophil activity [113-115].

Like zinc, bio reduced silver nanoparticle also has anti-inflammatory activity by decreasing the vascular endothelium growth factor (VEGF) level, deteriorate the expression of hypoxia inducible factor -1 alpha, suppress the production of pro-inflammatory cytokines like IL- 12 and tumor necrosis factor (TNF)-Alpha and also act to reduce COX-2 gene expression [116-119].

Sodium selenite metal salt has successfully been reduced by the green algae, *Ulva lactuca* and synthesized selenium NPs were tested on animal models and different positive results were observed. Selenium NPs successfully increase their antioxidant activity inside the cell which results in reduction of inflammatory responses. It also inhibits the PGE-2 (Activator) of pro-inflammatory cytokines like interleukin -6 and tumor necrosis factor -Alpha [120].

f) Anticancerous

NPs are well known for their target specificity, in therapeutics and disease diagnosis. Nano therapy is playing a pivotal role and success rates are quite high.

Nanotechnology has unfolded a new horizon in cancer biology and till date GSNPs are intensely being used in detection, diagnosis and testament of cancer of any type. Quantum dots, gold, silver, iron oxide NPs are first preference among researchers in cancer research.

In recent times silver NPs showed a promising result against several cancer cell line. Non-biogenic Ag NPs causes cytotoxicity among cancer cells by creating oxidative stress and reduced the viability of these cell lines. Green synthesized GSNPs has solved the problem to some extent. *Xanthomonas oryzae* (bacteria), *Fusarium acuminatum (*fungus) *Nelumbo nucifera* (plant) are all reported to synthesize silver nanoparticle which showed anticancer property.

Platinum (Pt) NPs are also reported to have anticancer activity. Extract solution of dates as a reducing agent was used to synthesize platinum NPs as dates are rich in antioxidants.

Anticancer properties of Platinum NPs are tested against hepatocellular carcinoma (HePG-2), breast cells (MCF-7), and colon carcinoma cells (HCT-116) with the help of MTT method [125].

Endophytic fungi that share mutualistic relationships with plants are very popular these days as a reducer to synthesise NPs. Endophytic fungi along with plants and animals and microorganisms are a very good option for the synthesis of any kind of metallic NPs because these fungi grow rapidly and they secrete enzyme extracellularly. An endophytic fungus *T. purpureogenus* isolated from leaves of *Pinus densiflora* plant, was used to synthesize silver NPs which showed promising results and potential cytotoxicity against a cancer cell line A 549 (Adenocarcinoma human alveolar basal epithelial cell) [126]. Au NPs synthesized from the endophytic strain *Fusarium solani* isolated from a plant *Chonemorpha fragrans* are successfully utilised to prevent proliferation of cancerous cells [127].

C] Pollution control

The unwanted involvement of any particles in air, water, soil causing different kind of diseases in human beings is literally called pollution. The 20th Century was facing its biggest problem regarding pollution before the world locked it down because of COVID-19 outbreak. Involvement of nanotechnology and ENPs in pollution control to keep the environment clean is no doubt one of the novel approaches of scientists globally.

a) Water pollution

Nano-fibres electrode made with AgNPs can be used to disinfect underground water source as these fibres act as selectively permeable membrane and purify water by hindering the presence of viruses, bacteria and other macromolecules [128, 129]. Some ENPs has hydro dehalogenation capacity which can be used to remove the organic and inorganic water contaminants from water. Nutt et al in 2005 reported that tricloroethane, a harmful water pollutant mostly present in the waste water released from industries can easily be isolated by using Cu, Ag like GSNPs [130]. Iron oxide GSNPs have also been used to remove the metals present in contaminated water [131, 132].

b) Air pollution

Use of nano-crystals to remove the air pollutants has already been established by researchers. Industrial smoke releases lots of hazardous gases among which the volatile organic compounds can be removed by nano MgO_2 incorporated nanofiber crystals [133]. Another air pollutant removal of ENPs is carbon nano tube (CNT) which is popularly used to prepare nanostructured membrane that can potentially prevent the release of methane, CO_2 and other harmful gases from automobiles, industries to the environment. It is already proved by J. Zhu that CNT can trap the greenhouse gases emitted from power generation and coal mining [134]. The waste collected in diesel emitted system through the nanostructured membrane filter again can be used to generate CNT filter using a technique of laser vaporization [135] which is very much-effective and eco-friendly.

c) Soil pollution

Nowadays ENPs are successfully used for removal of different soil pollutants from contaminated soil in a time saving, cost effective way [136]. Graphen oxide NPs, the oxidative from of graphene exfoliated from the chemical graphite has been used to remove metals and other toxic substances from muddy soil [137,138]. Fe NPs can potentially reduce the availability of as and other hazardous metals like Pb, Zn, Cd, Cu etc from contaminated soil [139].

d) Removing oil spill:

Every year a huge quantity of oil spill is reported globally [140] and technology related to use biological materials, chemicals, gelling substances etc. have successfully been applied to overcome the situation. Very recently potassium-magnesium based nanowires play a role to absorb the oils and reject the water through its water repelling coat [141] and finally recover the oil [142, 143].

D] Agricultural sectors

a) Enhancement of crop production

Inclusion of nanotechnology in agricultural sectors create a new era when a crisis appears in crop field due to indiscriminate use of different kinds of fertilizers, insecticides etc. to meet the huge production demand of the growing world. Nowadays different GSNPs are used in plant growth and development, enhancement in absorption of nutrient uptake mechanism, plant disease protection and application directly in the field as nano fertilizers [144-148]. It has been proved in various studies that multiwalled carbon nano tubes (MWCNTs) and oxidized MWCNTs (OMWCNTs) have a magic ability to influence seed germination rate and plant growth. [149]. The maximum germination rate in tomato, hybrid Bt. cotton, *Brassica juncea*, *Phaseolus mungo* and rice was observed with MWCNTs [150-152, 148]. Single walled carbon nano tube (SWCNTs) can initiate root elongation in Allium cepa and Cucumis sativus [153]. Khodakovaskaya et al, 2012 [154] reported that 5 – 500 µg/mL dose of MWCNTs can induce growth of Nicotiana tabacum cell culture by regulating marker genes. It was observed in case of Vigna radiata that suspension or foliar application of ZnO NPs at a dose of 20 ppm was effective for biomass enhancement [155]. Application of sulphur NPs is also helpful for dry weight enhancement of Vigna radiata. Prasad et al at 2012 noticed that application of ZnO NPs at a particular dose enhance germination percentage, overall biomass and fruit yield of *Arachis hypogaea* as well as increase dry weight while applied on *Vigna radiata*. Another study revealed that lower dose of ZnO NPs increased germination and growth in onion [156]. Application of 60 ppm AgNPs on Phaseolus vulgaris is beneficial in respect to root-shoot length and overall dry weight enhancement [157]. Kumar et al, 2013 [158] observed that application of GNPs on *Arabidopsis thaliana* increased germination percentage and root length. Another study revealed that application of aluminium oxide NPs on *Arabidopsis thaliana* enhances root length [159, 160]. Alumina NPs can also enhance biomass accumulation and root length in *Lemna minor* [161]. Application of iron oxide NPs on Glycine max increased production yield [162] while ZnFeCu-oxide suspension enhance biomass of Vigna radiata when applied in proper dose [163]. TiO_2 NPs enhanced seed germination and promoted radicle and plumule growth of canola seedlings and *Foeniculum vulgare* respectively [164, 165].

b) Involvement in plant pathogenicity:

Implication of ENPs in crop protection is the most advanced application in agriculture to save and secure the production. In this perspective, application of GSNPs is very promising. Silver (Ag) NPs is strongly effective to destroy hyphal nature of fungi by damaging the fungal cell wall configuration. AgNPs shows toxic effect against Gm+ and Gm- bacteria and when it is mixed with erythromycin, kanamycine like antibiotics the toxicity rate increases [166, 167].

AgNPs are the most potential ENPs against any kind of plant pathogens viz. different fungi species of *Alternaria*, some species of *Sclerotium*, *Trichosporonasahii sp, Magnaporthe grisea, Macrophomina phaseolina, Rhizoctonia solani, Botrytis, Curvularia lunata* etc [168-172].

Pariona et al in 2019 [173-175] reported that Cu NPs can generate reactive oxygen species (ROS) and degenerate hyphal nature of some plant pathogenic fungi named *Fusarium* and *Neofusicococcum* sp which attack many forest plants as well as crop plants. Ag NPs also have good bactericidal effect against some species of *Bacillus*, *Staphylococcus*, *Salmonella*, *Protea*, *Listeria* by causing the disruption of fungal cell cytoplasm from the cell wall. Like AgNPs and Cu NPs, some other GSNPs like ZnO NPs, Si-Ag NPs have successful fungicidal activity and can be used to prevent conidiophore development and subsequent hyphal spread [176-182]. Fe, Fe_2O_3, Ag and MgO GSNPs have potentially been used against some species of *Staphylococcus*, *Bacillus*, *Pseudomonas*, *Xanthomonas*, *Azotobacter* in moderate to high efficiency [183-188].

At present an emerging solution has developed by involving nanotechnology to prepare nano pesticides and nano fluids [189]. Moving to a broader concept of nano-enabled technology and building on the experience from other sectors (e.g., food science, nanometrology) will be more valuable to support the development of more sustainable agrochemicals [190]. NFs have more availability to plants as they can enter easily through the nano-pores and stomatal openings in plant leaves.

Nano herbicide and nano pesticides are also much effective in crop plants than the market available insecticides [191, 192]. Besides all these, GSNPs may have the capacity to develop biomarker for detecting plant pathogenicity and nano chip-based biosensor through which hybridization or GM crop production can be easily detected [193-196].

E] Environmental remediation (Heavy metal detection):

Heavy metals viz. osmium (Os), mercury (Hg), led (Pb), cadmium (Cd), arsenic (As), chromium (Cr), thallium (Tl) present in our ecosystem enter into our body through the food we consume, the water we drink, the air we breathe and then accumulate in our vital organs and disrupt the function of heart, brain, kidney, liver, bone, etc. So, the detection of heavy metals is very crucial. GSNPs are very faithful in this regard as they cannot do any contamination after their final disposal in our environment [197-202].

As metallic NPs are very flexible in the aquatic environment so they are widely used in different applications related to water purification. Some bimetallic NPs, Iron oxide NPs are very popularly used to reduce chlorinated and brominated contamination from water and other heavy metals like Cu, Co, Ni, Cd, etc [203-208]. Nanotubes made from titanate can remove gaseous nitric oxide [209]. AgNPs and some metal-doped TiO_2 can purify contaminated water by removing endotoxins, some hazardous bacterial strains, phenanthrene, pathogenic hepatitis B virus, and water spoiling *E. coli* [210-216]. SiO_2 also interact with contaminants nicely and remove gaseous CO_2, H_2S, aldehydes, ketones [217-224] as well as heavy metals, cationic dyes from wastewater [225-233]. Nanotubes and nanofibers of titanate can remove the most fatal radioactive cesium and iodine ion from contaminated water [231]. Graphene and graphene composite are much used to purify contaminated water by removing gaseous benzene, heavy metals, fluoride, etc. [234-237]. The good adsorption property and photocatalytic nature of SWCNTs and MWCNTs involve them in remedial activities [238, 239]. Moreover, the CNTs act as inert material when reacting with different contaminants and it is quite safe to use the above-mentioned NPs prepared through the green route as the remnants after their use remains in a non-hazardous state. Polymar-based NPs viz. polyamine modified cellulose, dendrimers, amine-modified polyethylene glycol are mostly used to remove hazardous chemicals viz. manganese, arsenic, different heavy metals, organic polymers like pharmaceutical residues, aromatic and aliphatic hydrocarbons, volatile organic substances, harmful gases like CO_2, SO_2 and the biological contaminants like parasites, bacteria, fungal and algal contaminants etc. [240-246].

F] Cosmetic Industry

a) Cosmetic production

For sunscreen production, ZnO NPs with a particle size of ≥ 20 nm were successfully used for many years as prevention of UV rays with an insignificant effect on the cutaneous membrane of our skin [247]. Many other quantum dots, nanotubes, fullerenes, and different nano-capsules are applied for the same purpose [247]. To provide better longevity of the active ingredients of the cosmetic products, nanoscale droplets are mixed and depending on the preparation technique the structure of the nanodroplets can easily be manipulated [248, 249]. Nowadays, solid lipid NPs are used in cosmetics as they help in control release of the active components of the product and express its effect for a long-time improving penetration potentially through our skin [250– 252]. Petersen in 2008 reported that some nanocrystals may give a better effect of cosmetics when applied due to some special physical and chemical properties of nano-aggregated nanocrystals [253].

Due to the superb antibacterial activity of Au and Ag NPs are used extensively in skin care products, perfume preparations, and in toothpaste formulation [254]. Ag NPs are also used to prepare nail-care and lip -care products [255-257].

1 nm particle size of Buckminster fullerenes or buckyballs (C60) is a very good scavenger of free radicals and for this they are used in some very expensive skincare products [258].

b) Cosmeceuticals

The involvement of ENPs in cosmetic production is not new in the 21st century but the incorporation of GSNPs in cosmeceuticals is undoubtedly opening a new era when therapeutic efficacy with biological ingredients will be much promising for the users [259, 260]. Different NPs are used as nanocarriers in cosmeceuticals to deliver the active ingredients of the cosmetics among which the most popular ones are liposomes, niosomes, dendrimers, nanosphere, cubosomes, polymersomes [261]. The drug encapsulated by liposomes can be used to release both the hydrophobic as well as hydrophilic ingredients, size ranging from 20 nm to few micrometers in its unilamellar and multilamellar configuration [262, 263]. Liposomes are very frequently used in shampoo, moisturizers, face cream as they are biodegradable and non-toxic [264]. Vegetable phospholipids are used for topical applications in cosmetics surgery and to solve different dermatological issues [265, 266]. Flexible liposomes are used to reduce skin wrinkles and to increase skin smoothness [267].

Niosomes were first introduced by the famous cosmatics production brand L'Oreal and they got patent on it under the trade name L ancome in the year 1987 [268]. Niosomes are good carriers for those drugs which have low adsorption ratio and enhance to reach the active components to targeted site with greater efficacy [269, 270].

Biodegradable and non- biodegradable nanospheres are used in anti-wrinkle, anti-aging, and anti-acne creams as they can penetrate all skin layers and act from the base of the cream make its advance involvements in hair-care products, hair gels, sunscreen, acne preventive skin products [271].

Dendrimers as its variable structures, biocompatibility, controlled release, and controlled size

The inner hydrophobic core encapsulated by the outer hydrophilic layer of polymersomes makes their use in cosmeceuticals to deliver some drugs that are needed during surgery or other therapeutical skin treatments [272, 273]. Depending on the necessity for membrane permeability the varied particle sizes and molecular weight of polymersomes help dermatologists to treat with advanced nanotechnology [274, 275].

Cubasomes having a size range from 10-500 nm can carry to separate regions of water divided by desired surfactants (not clear) by its special cubic liquid phase [126]. Cubasomes are most popular in plastic surgery as their potential to release drugs in the control method to its targeted sites [276, 277].

G] Food technology

The biocompatibility and non-toxic nature of AgNPs involve it successfully in food packaging and food preservation for a longer time than the marketed processor [278, 279]. Its antibacterial nature also helps to prevent foodborne bacteria development [280]. During food packaging, polymeric silica nanocomposites can enhance mechanical strength and heat resistance capacity as the nanocomposite have the potency to develop a gas barrier [281, 282]. Some other nanocomposites can create hydrophobic as well as a gaseous barrier surrounding the packaging system and indirectly enhance the shelf life of the packaged food [283]. Two to three-layered nano-laminates are recently used on food coating because of its easy to break nature [284-286].

The good antibacterial property of TiO_2 and Ag NPs with the high surface area makes them have better access to bind with food packing [287, 288] and also as a food additive [289]. TiO_2 combining CNT is also used in the food industry for demolishing Bacillus spores with high efficiency [290]. CNT is also used for membrane separation of proteins, fats, vitamins, and the detection of antibodies, DNAs, enzymes, proteins, etc [210, 292].

ZnO NPs are also used to prevent activities of both Gram + (*Bacillus* sp.) and Gram – (*E. coli)* bacteria of processed food [293]. Zn NPs also show antifungal activities against *Penicillium expansum*, Botrytis, etc, and used popularly to save the food from such fungal infection [294]. Platinum and gold, the two costly metallic NPs are used as good bio-sensor during food analysis in food technological industries [295]. SiO_2 and CNT both are also used as a food additive [296].

Meat and fish spoilage are successfully indicated by berryline -based nanofibrils by detecting the gaseous amine present in it [297].

H] Energy conversion:

The application of ENPs in solar cells is very common in the 20th century. The most popular energy conversion machinery developed by using ENPs is photovoltaic cells where the light source of the Sun is directly converted to electrical energy [298]. Semiconductor ENPs like ZnO NPs, TiO_2, SnO_2, MnO_2, RuO_2, are most frequently used to prepare solar cells as well as storage devices [299-302]. Carbon-based nanomaterials like SWCNTs, MWCNTs, fullerenes, graphene is used to prepared electrodes for photovoltaic solar cells [303, 304]. The energy conversion efficiency of dye-sensitized electrochemical cells can be highly improvised by involving ZnO quantum dots, oxidized MWCNTs [305, 306]. ZnO quantum dots are also effective for the conversion of heat energy to electrical energy as well as to enhance the storage capacity of the cell [307].

I] Construction Industry

Recently the application of ENPs in the construction industry creates a revolution in making stronger, long-lasting building materials, waterproof nano-coating, nano-paint wall colour, etc [308, 309].

Cu and CuO NPs are used in the formability of steel, develop corrosion-resistant materials, and also to enhance welding ability. The anticorrosive and photocatalytic nature of TiO_2 and SiO_2 make their abundant use in concrete material [310]. CNT is also used as a nanofiller in concrete [311] and nano Al2O3 incorporated cement shows high-temperature tolerance capacity [312].

Recently NPs are being used to improve efficiency and to provide new functionalities to the paints. There are already several nano-enhanced paints on the market. TiO_2, Ag, Au, Zn, SiO_2, and other GSNPs are used to prepare nano paints as these paints are easy to clean, UV-protected, water repellent, scratch resistance, fire retardant and after all shows anti-bacterial and anti-fungal property [313-315].

Pros and cons

The use of the biological route for the synthesis of NPs reduces or eliminates the hazardous inclusion of chemicals during the processing period and finally produces environmental benign, low cost, homogenous NPs for wide and safe application in various sectors to fulfil the human need. GSNPs is easy, efficient, and eliminate the use of toxic chemicals by consuming less energy. The products and by products after using GSNPs always remain safe. The GSNPs are highly stable and already well-characterized by researchers and their stability able them to involve in many applications where non-biogenic NPs shows limitations due to toxicity. The major advantages of GSNPs over NPs are the shape and size, the two most important features that make them easy to control in case of GSNPs by altering the concentration of biological substrates, pH, temperature, mixing speed, and exposure time. High temperature, pressure, and toxic chemicals can be avoided during GSNPs synthesis and above all microbial synthesis is more advantageous as we can prepare NPs by maintaining the culture only instead of laborious chemical processes. After all, the rich biodiversity of various biological components has been explored for GSNPs genesis that provides a new possibility of synthesizing NPs using natural reducing and stabilizing agents.

Another major advantage of GSNPs over NPs is that GSNPs are biodegradable and henceforth safer to use in pharmaceutical and biomedical products. The biocompatible and biodegradable nature of GSNP helps them to enter in the cosmeceuticals as they are easy to penetrate through the dermal layer without significant side effects.

The controlled release of GSNPs in microsphere, microcapsule, coated granules helps a lot against plant pathogenicity and thereby protect the active ingredient from biodegradation and unwanted leaching. In agriculture, GSNPs can directly be used as nano fertilizer, growth enhancer and in crop protection shows better results by avoiding the fertilizers and pesticide available in the market.

Applications of Copper NPs have been very popular because of its strong anticancer and antibacterial property and has a low production cost. Green synthesized Cu NPs have shown a higher rate of cytotoxicity against particular cancer cell lines because smaller the size of the NPs, it is easier to penetrate inside the cell and cause cytotoxicity.

Places where food storage faces problems because of proper cooling, GSNPs are used to resolve the problem allowing longer and safe storage of food materials. GSNPs mediated remediation of the polluted environment is speedier and often cost-effective compared to the conventional methods and continuous environmental monitoring can be reduced by using GSNPs as nano-sensors where hazardous releases are insignificant. Applications of GSNPs in the biomedical industry and drug formulation provide safe, non-toxic recycling of by products and eco-friendly disposal of waste materials.

However, some limitations still have to be resolved. The plants used to prepare NPs cannot be manipulated as the choice of NPs are decided through optimized synthesis and genetic engineering. In the case of phytogenic synthesis, plants often produce a low yield of secreted proteins which may decrease the synthesis rate of GSNPs. In pharmaceuticals, some GSNPs have limitations as they are costly to produce, low soluble, susceptible to leakage of drug or loading lesser drug, showing osmotically sensitive, and having inadequate stability. Finally, nano-mediated applications are very sensitive and in all cases dose dependent also. Therefore, we will need to use with proper expertise to handle the confusion arising due to concentration regulations of GSNPs.

Concluding remarks

A great surge in research and development of GSNPs has shown that these new materials can be used in human endeavours. However, the full potential of their applications explored in different fields creates another area to learn about the benefits and limitations of these biogenic NPs for sustainable development.

We report here the main conclusions from our review, aimed towards the inclusion of GSNPs with their applications in various aspects of life. Increasing applications of GSNPs-based nanotechnology in different fields in recent times has stimulated extensive debates about the effect of the GSNPs on the environment as all the living beings of the ecosystem, respond to the intrusion of such tiny particles in the environment. GSNPs have many advantages over non-GSNPs as the previous ones are environmentally benign, homogenous, cost-effective, easy to synthesize, and easy to handle. Thus, using GSNPs, we have arrived at some important conclusions regarding the role of these NPs on biomedicine and therapeutics, pollution control, environmental remediation, energy conversion, agricultural sectors, food industry, cosmetics production, construction industry, electronics industry with immense possibilities and can be put to use in every aspect of our daily lives. The advantages of introducing these GSNPs in different areas replacing non-biogenic NPs will definitely enrich our knowledge in a field that is so complex, so mysterious and yet so relevant.

Declaration of interest

There are no conflicts to declare.

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