



Metallic and non-metallic nanoparticles from plant, animal, and fisheries wastes: potential and valorization for application in agriculture

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Abstract

Global agriculture is facing tremendous challenges due to climate change. The most predominant amongst these challenges are abiotic and biotic stresses caused by increased incidences of temperature extremes, drought, unseasonal flooding, and pathogens. These threats, mostly due to anthropogenic activities, resulted in severe challenges to crop and livestock production leading to substantial economic losses. It is essential to develop environmentally viable and cost-effective green processes to alleviate these stresses in the crops, livestock, and fisheries. The application of nanomaterials in farming practice to minimize nutrient losses, pest management, and enhance stress resistance capacity is of supreme importance. This paper explores innovative methods for synthesizing metallic and non-metallic nanoparticles using plants, animals, and fisheries wastes and their valorization to mitigate abiotic and biotic stresses and input use efficiency in climate-smart and stress-resilient agriculture including crop plants, livestock, and fisheries.

Keywords Abiotic and biotic stresses · Crop, animal, and fisheries wastes · Nanostructured materials · Mitigation · Valorization

Introduction

Agriculture globally has shown appreciable growth in the last few decades, meeting the demand for food for the growing population. Growth in the agricultural sector in terms of “development objective” is considered a crucial element in developing countries because more than 60% of the population directly or indirectly depends upon agricultural

production to earn their living (Raieszadeh et al. 2013). Similarly, livestock and fish farming, including aquaculture, are important allied activities to agriculture worldwide. These sectors play a vital role in providing food and nutritional security and hold the key to enhancing the livelihood of the poor farmers. Aquaculture water comes from one source or a combination of several sources such as groundwater, surface water (freshwater, brackish water, and seawater), and an alternative source (rainwater). Based on salinity, aquaculture is classified as freshwater aquaculture, brackishwater aquaculture, inland saline aquaculture, and mariculture (Fig. 1). Besides, there is a vast potential of reservoirs and wetlands for enhancing fish production through culture-based fisheries or reservoir fisheries.

Diversification and improvement of agricultural production in terms of field and horticulture crops, dairy, goatery, poultry, and fisheries along with household-based other off-farm activities such as backyard farming/kitchen gardening supported by technological innovations can fuel the economy of the rural areas through livelihood improvement. Integrated agri-aquaculture is family-based, the zero-budget farming systems involving synergies among farm enterprises

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Freshwater fishes and shrimp

Indian major carps



Labeo rohita



Catla catla



Cirrhinus mrigala



Heteropneustes fossilis



Pangasius pangasius



Macrobrachium rosenbergii

Brackishwater / Coastal aquaculture Fishes and shrimp



Lates calcarifer



Chanos chanos



Etroplus suratensis



Sella serrata



Penaeus vannamei



Penaeus monodon

Fig. 1 Candidate species for freshwater, inland saline, brackishwater/coastal aquaculture

with the advantages of using animal manure, crop by-products, pond sediments, and aquaculture wastewater as pond fertilizer, and supplementary feed for fish, fertilizers, and irrigation for crop plants respectively, ensuring higher food production, environmental conservation, and food security.

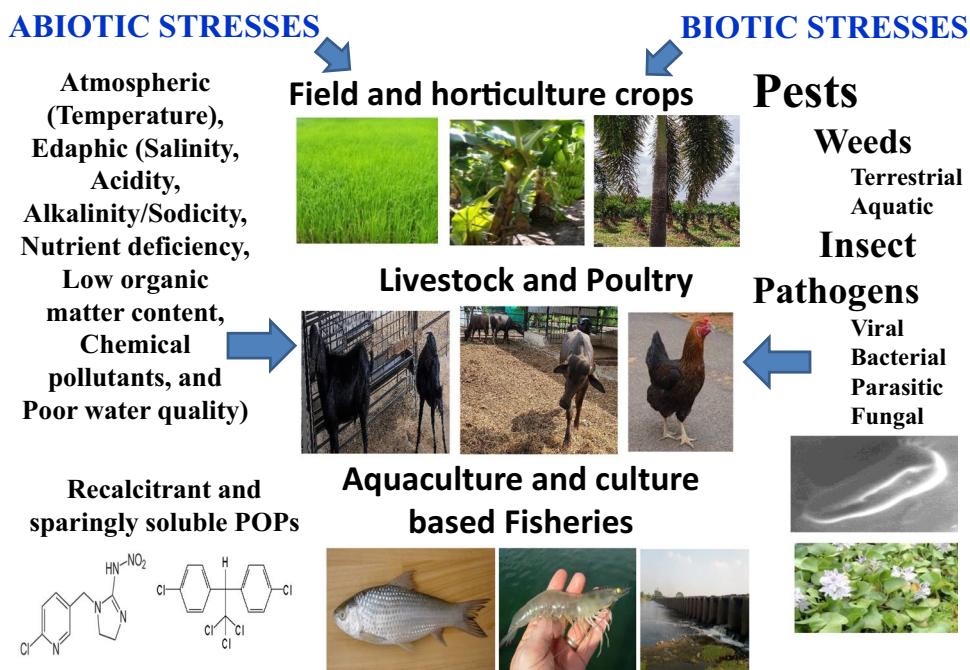
In the coming decades, climate change is the major constraint for the crop, livestock, and fish production, and its adverse effect on the degradation of land, soil, and water quality and related environment can hinder the growth of the agricultural sector, which is expected to affect the farmers severely. Furthermore, abiotic stresses like elevated temperature, salinity, acidity, alkalinity/sodicity, nutrient deficiency, chemical pollutants, and poor water quality have gradually increased, leading to major agricultural production limitations (Fig. 2). Also, biotic stresses of bacterial, viral, parasitic, and fungal pathogens are adversely affecting agricultural production.

After years of the green revolution, the agricultural sector faces a decline in agricultural products regarding world population growth. In recent years, soil pollution and agricultural land degradation with hazardous compounds present in urban and industrial wastewater are the

most important factors limiting food crop production in the world (Mousavi and Rezaei 2011). Moreover, the sector has to deal with many other concerns like depleting nutrients in the soil, accumulation of pesticides and fertilizers, and sustainable use of natural resources (Ali et al. 2017). Agricultural research and development have made a significant contribution in the past. The implementation of technological innovation has a major role to play in enhancing agricultural production and ensuring food security. Therefore, it is the apparent necessity to adopt new technologies that can shape modern crop farming in a more productive way that would finally lead to precision agriculture and ensures the supply of the right amount of input at the time of need (Prasad 2012).

Ameliorating conditions of abiotic and biotic stresses is a critical aspect in the context of sustainable production. Mitigating these stresses using ineffective conventional methods is a significant challenge. Innovative nanotechnological approaches have emerged with diverse applications in the rapidly emerging field of the global food sector for human and animal welfare, and medicine and have potential applications in agriculture. The potential of nanotechnological

Fig. 2 Abiotic and biotic stresses affecting crops, livestock, and fisheries



intervention is incredible concerning livestock. It resolves many other issues related to livestock production, animal health, reproduction, and maintaining hygienic practices during the rearing period of the food animals. However, the application of nanotechnology in agriculture and forestry is likely to have several environmental, health, and economic benefits as it offers the opportunity for the safer and effective administration of fertilizers, pesticides, and herbicides, and the nanostructured materials also help to eliminate the toxic components from the agricultural ecosystem (Kuzma and VerHage 2006).

The increasing consumption, as well as wastes of pharmaceuticals and personal care products (PPCPs), including analgesic, mucolytic, and antibiotic, antiviral, and inflammatory drugs, raises concern about their potential threat to humans, agriculture, and aquatic and wildlife in different environments. Even though PPCPs as well as their metabolites and residual drugs are found in low concentrations in the freshwater ecosystem, the majority of them are physiologically active, leading to antimicrobial resistance. Therefore, the complete degradation of these broadly used PPCPs into non-toxic end products is highly crucial. With the increasing resistance of bacteria to antibiotics, nanometals have again become popular and are one of the promising candidates for controlling the side effects of PPCP wastes on the environment. The application of suitable nanomaterials in photocatalytic and environment-friendly degradations of the various drugs by suitable catalysts within the treatment site of the pharmaceutical industries has been recommended as one of the effective methods for reducing the irreversible

side effects of the wastes on the environment (Ebrahimi and Akhavan 2022).

Nanoscience represents innovative platforms that ensure the provision of a broad range of novel and advanced technologies for environmental, biological, and agricultural applications. A robust and environmentally viable process for synthesizing metallic nanoparticles is an essential step to advancing nanotechnology. The cost-effective synthesis of metal nanoparticles is a vast area of research due to their potential applications in developing novel technologies. Physical, chemical, and biological methods have been developed to synthesize metallic NPs of various shapes and sizes. Among those, biological method is an economically and environmentally viable alternative to physical and chemical approaches.

The inclusion of nanotechnologies in agriculture production and post-harvest processing and preservation confronts a new edge that deserves attention. Input use efficiency and stress mitigation in crops, livestock, and fisheries is an emerging area of agricultural research. There is a need to use inputs such as fertilizers, pesticides, antibiotics, and nutraceuticals in such a way that wastage will be minimized for efficient utilization and to make the final product economically viable. The development of a nanodelivery controlled release system for these kinds of inputs may address the problems of their application in agriculture at the commercial level.

This review paper explores the innovative methods for synthesizing nanostructured materials using plants and animal wastes and their valorization to mitigate abiotic and

biotic stresses and input use efficiency in crops, livestock, and fisheries.

Circular bioresource utilization for the synthesis of nanoparticles

The circular economy is based on the concept of producing more from less, turning waste into new resources by optimizing production and consumption systems, besides losing nutrient loops and reducing harmful discharges to the environment. This involves smart and efficient use of resources, minimizing and repurposing waste. Valorization of agri-food wastes/by-products or value addition currently considered waste and discarded can provide a second life to products, which is a core aspect of the circular economy.

The synthesis of metallic nanoparticles using food wastes and their aquaculture applications has recently gained considerable attention with the biological method of synthesis being the most effective and environmentally viable method. Generally, chemical processes used for the synthesis of nanoparticles are toxic, flammable, and adverse in various applications. However, green synthesis is a better alternative due to its environmental viability, non-hazardous, and safe application in fisheries. The agro-food industries are one of the most significant production sectors worldwide, with a turnover of US \$4 trillion per year (Tekiner et al. 2015). Recently, the management of food waste processing has emerged as a major constraint. Within the past few decades, extensive research has been conducted to explore innovative methods for synthesizing nanostructured materials using

extracts and wastes from field crops, horticulture crops, livestock, poultry, aquaculture, and fisheries. The research has paved the way for exploring the interactions among various systems including physical, chemical, biological systems, agro-food, and nutrition sectors. There is excellent potential to enhance food quality and constituents such as nanoparticulate delivery systems, food safety, and biosecurity (Tekiner et al. 2015). Schematic details of circular economy applied to the synthesis of nanostructured materials using plants, livestock, and fisheries are presented in Fig. 3, and their valorization for potential applications in agriculture is presented in Fig. 4.

Synthesis of nanoparticles using plant wastes (field/horticultural crops and plantations/tree)

Silver nanoparticles

India produces a total of 500 million tons (Mt) of agricultural crop residue every year. The utilization of agro-wastes for the production of value-added products such as biochar, organic fertilizer, nanoparticles, biogas, and pulp may significantly level out the issue of management of agricultural waste. Plant extracts and lignocellulosic agro-waste-based products have been used for the bioremediation of nitrogenous and heavy metals in aquaculture systems and related aquatic environments (Krishnani et al. 2002, 2003, 2004, 2006a, b, 2008a, b, 2009a, b, 2012, 2013a, b, 2015a, b, 2018, 2019; Krishnani and Ayyappan 2006; Parimala et al. 2004, 2007). Recently, nanomaterials opened a green approach to solving current environmental issues. However, conventional

Fig. 3 Circular economy-based synthesis of nanostructured materials

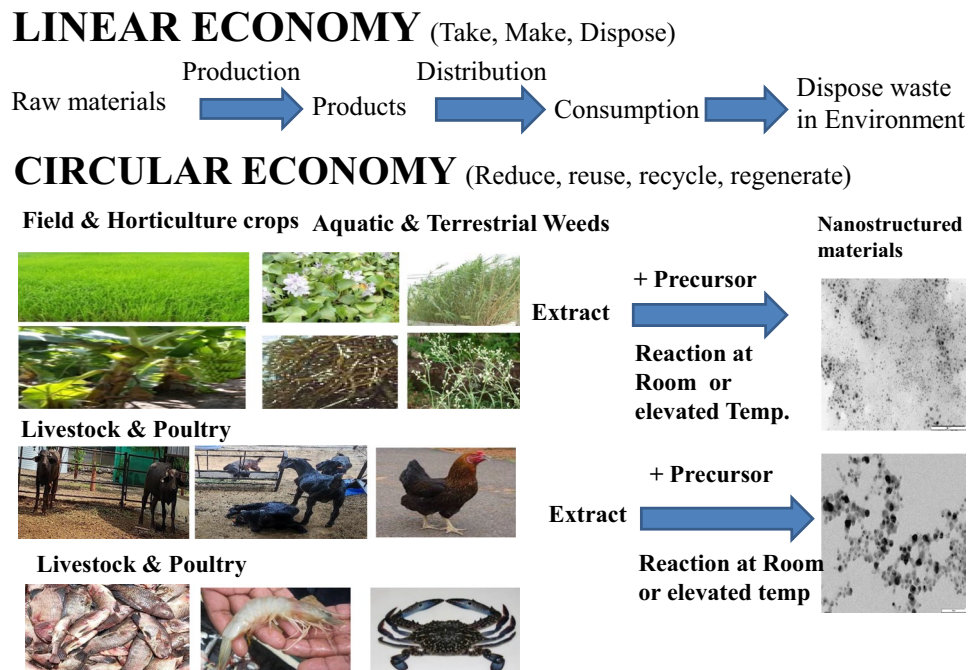
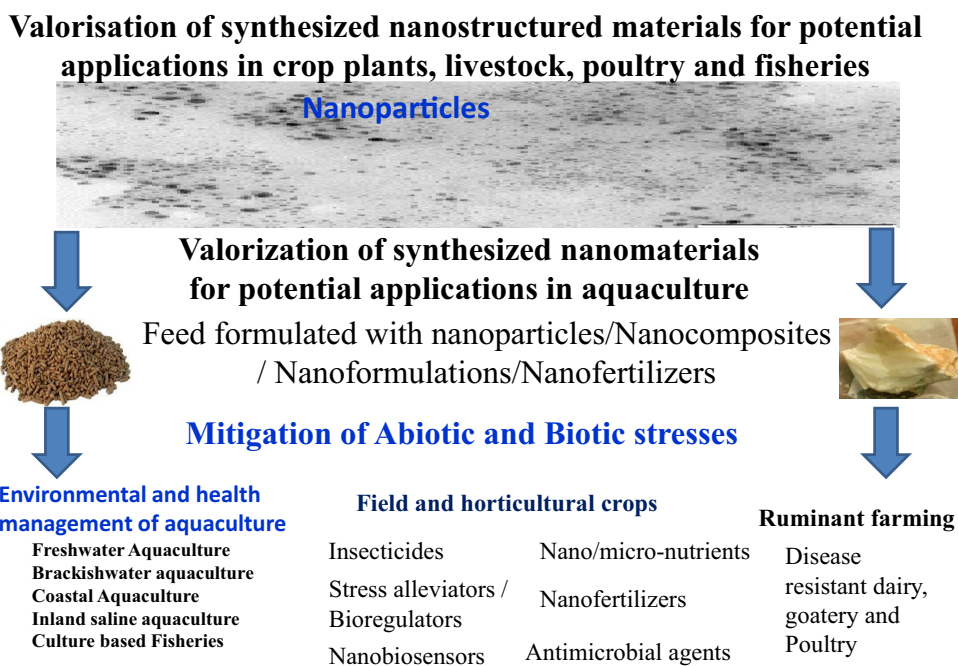


Fig. 4 Valorization of synthesized nanostructured materials for their applications in crops, livestock, and fisheries



NP synthesis requires the use of toxic chemicals and generates organic wastes. Hence, in recent years, plant-mediated and biomolecule-derived synthetics have gained much attention. It is estimated that about 95% of rural and 70% of urban births in developing countries are dependent on traditional medicines for pre- and post-maternity care (Nasar et al. 2019). There is undoubtedly an urgent need to assess the indigenous knowledge of rural communities associated with the ethnobotanical species and indigenous scientific evaluation of our original medicinal plants in today’s scenario. It is expected that many biomolecules of indigenous plants may prove important as an alternative to hazardous chemicals during the synthesis of nanostructured materials. A recent medicinal plant application involves the use of plant extracts as reducing agents for the green synthesis of metallic nanoparticles. The plants mediated synthesis of nanoparticles has gained tremendous interest. Plants and their extracts are preferred over other biological sources for green synthesis due to their rich contents of bioactives. The synthesis of nanoparticles using plant extracts have an edge over other biological syntheses. A plant extract dispenses with the maintenance of bacterial, fungal, and algal cultures. Plant extracts contain bioactives including phenols, flavonoids, and terpenoids implicated in the bioreduction of metal into NPs (Ovais et al. 2018).

Various plant extracts have been used for the green synthesis of nanoparticles. Agricultural waste materials (field/horticultural crops and plantations/tree) used in the synthesis of silver nanoparticles (AgNPs) and their applications to alleviate abiotic and biotic stresses are presented in Table 1. One of the important challenges during the outbreak of

diseases is increasing herbal medicine waste. A variety of bioreducing agents used for nanosynthesis can lead to the production of nanoparticles having distinct characteristics including shapes, sizes, and bioactivity (Saratale et al. 2018a) for potential applications in biomedicine, pharmacology, food science, agriculture, and environmental remediation. Saratale et al. (2017, 2018b) synthesized silver NPs using leaf extracts of medicinal plants, which exhibited enhanced positive synergistic response against food-borne bacteria and phytopathogens, useful to prevent food deterioration, as well as being useful in food packing applications. Jouyandeh et al. (2022) employed subcritical hydrothermal treatment of herbal medicinal waste for the extraction of organic acids, amino acids, and sugars.

Recent advancements in developments in the cleaner green biosynthesis of metal, metal oxide, and magnetic and quantum dot using plants or plant extracts, and phytochemicals have been regarded as safe, non-toxic, consistent, biologically compatible, and environmentally viable bottom-up approaches, where atoms or molecules are brought together into molecular structures in the nanometer scale dispensing with hazardous chemicals such as organic solvents, reducing agents, and stabilizers (Velusamy et al. 2016). In general, the prominent role of polyphenols followed by other biological constituents, such as alkaloids, carboxylic acids, glycosides, polyols, ascorbic acid, terpenoids, tannins, amino acids, and flavonoids was observed in extracts from different parts of the plants including leaf, root, latex, fruit pericarp, fruit juice, seed, and stem used in the nanosynthesis involving reduction, capping, and stabilization of metal NPs having antibacterial, antidiabetic, and antioxidant radical

Table 1 Agricultural waste materials (field/horticultural crops and plantations/tree) used in synthesis of silver nanoparticles and their applications in mitigation of abiotic and biotic stresses

Waste/material used	Capping and stabilizing supplemented material	Function	References
Field and horticultural crops			
Wheat bran xylan	Xylan	Free radical scavenging activity	Harish et al. (2015)
<i>Annona squamosa</i>	Peel extract	Antioxidant	Kumar et al. (2012)
Citrus	Cellulose	Antibacterial, free radical scavenger, bioremediation	Ali et al. (2017)
<i>Citrus sinensis</i>	Orange waste	Antimicrobial activity	de Barros et al. (2018)
Cacao extract	Biomolecules	Antimicrobial activity	Chowdhury et al. (2016)
Lychee fruit	Peel + antibiotics	Antibacterial	Perveen et al. (2018)
Cochineal dye and pomegranate peel	Peel extract	–	Goudarzi et al. (2016)
Watermelon rind	Rind	Antibacterial, antioxidant	Patra et al. (2016)
Coconut shell	Shell extract	Antibacterial against <i>S. aureus</i> , <i>L. monocytogenes</i> , <i>E. coli</i> , <i>S. typhimurium</i>	Sinsinwar et al. (2018)
Citrus and kinnow	Peel extracts	Biomedical	Naz et al. (2017)
<i>Pisum sativum</i>	Outer peel	Biomedical	Patra et al. (2019)
Beetroot	Aqueous extract	Antibacterial and catalytic activity	Bindhu and Umadevi (2015)
Tree/plantations			
Plants' leaf	Leaf extracts	Therapeutic agent against <i>A. hydrophila</i>	Mahanty et al. (2013)
<i>Anabaena doliolum</i>	Cell extracts of cyanobacterium	Antimicrobial and antitumor activities	Singh et al. (2014a, b)
Eucalyptus	Leaf aqueous extract	Nanomedicine	Pourmortazavi et al. (2015)
<i>Prosopis farcta</i>	Leaf aqueous extract	Antibacterial activity against multi-drug resistant bacteria	Miri et al. (2015)
<i>Biophytum sensitivum</i>	Leaf aqueous extract	Catalytic activity in dye- Methylene blue degradation	Joseph and Mathew (2015)
<i>Eugenia roxburghii</i> DC	Leaf aqueous extract	Antibacterial against biofilm producing bacteria	Giri et al. (2022)
Medicinal and aromatic plants/herbs/ornamental shrubs			
<i>Lippia citriodora</i>	Leaf aqueous extract	Antimicrobial	Elemike et al. (2017)
<i>Aloe vera</i>	Aqueous extract	Antibacterial and Mosquitocidal properties	Dinesh et al. (2015)
<i>Argyrea nervosa</i>	Leaf Aqueous extract Bio-reducing agents	Antioxidant and antibacterial against food borne pathogens	Saratale et al. (2017)
<i>Ephedra procera</i>	AgNPs	Antimicrobial, antioxidant	Nasar et al. (2019)
<i>Lantana camara</i>	Aqueous extract of leaf	Antimicrobial activity	Ajitha et al. (2015)
<i>Taraxacum officinale</i>	Dandelion leaf aqueous extract Bio-reducing agents	Antioxidant and antimicrobial activity against phytopathogens	Saratale et al. (2018b)

scavenging activities (Iravani et al. 2014; Borase et al. 2014; Saratale et al. 2017, 2018b; Aswathi et al. 2022).

Plant extracts are usually rich in bioactive compounds, which act as the reductant, size controller, and stabilizer at room temperature. Ajitha et al. (2015) used *L. camara* leaf extract for green synthesis of stable spherical and capped AgNPs in the colloidal state with a zeta potential of -26.4 mV. Plants with well-known medicinal properties are extensively used for the shape and size-controlled synthesis of AgNPs (Zhan et al. 2011). The size of NPs is affected by several factors such as temperature, pH, substrate concentration, and time of exposure (Gericke and Pinches 2006). Among all metals, AgNPs received substantial attention due to their higher stability, catalytic potential, electrical conductivity, and large surface-to-volume ratio.

Silver tends to react with sulfur of the proteins present in biological membranes and phosphorus present in DNA more effectively. Nanostructured materials have significant potential in controlling pathogens associated with humans and animals. Currently, AgNP applications have the highest degree of commercialization among all the nanoparticles in consumer products due to their wider applications, ranging from medical devices, and home appliances to water treatment, and success and efficiency in combating various pathogens over the years. AgNPs are categorized as potent antimicrobial agents (Elechiguerra et al. 2005; Shahverdi et al. 2007), hence used for treating wounds and burns (Samuel and Guggenbichler 2004). They also act as growth promoters (Sarkar et al. 2015) and immune boosters as well (Beck et al. 2015) at limited doses.

Kumar et al. (2012) used agriculture waste—aqueous peel extract of *Annona squamosa*—to synthesize irregular spherical silver nanoparticles (35 ± 5 nm). A simple and reproducible method has been used for AgNP impregnation with cellulose isolated from citrus waste, which is used for the antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* (Ali et al. 2017). The AgNP-impregnated cellulose can be effectively used as a scavenger of free radicals at the wound site in wound dressing to prevent the bacterial attack and also as filters for bioremediation and wastewater purification.

Green synthesis of nanoparticles using seaweed is fascinating and gaining attention in biomedical applications. Ramkumar et al. (2017) synthesized functionalized AgNPs using an aqueous extract of seaweed *Enteromorpha compressa* as a reducing and stabilizing agent and demonstrated their biocompatibility for efficient antimicrobial and anticancer activities. Brown algae/seaweed *S. longifolium* contains a significant amount of reducing agents acting as bionanofactory for the synthesis of copper oxide nanoparticles (Aswathi et al. 2022). MgONPs are synthesized using aqueous extracts of brown seaweed *Sargassum wightii*, which are rich in polyphenols, carotenoids, amino acids, vitamins, and polysaccharides, acting as capping and reducing agents in the synthesis of MgONPs.

Elemike et al. (2017) reported the synthesis of AgNPs derived by aqueous leaf extract of *Lippia citriodora* at two different temperatures. Plant-derived AgNPs showed considerably higher antimicrobial activities than the crude plant extract against several tested pathogenic strains such as Gram-negative (*Escherichia coli*, *Salmonella typhi*) and Gram-positive (*Bacillus subtilis* and *Staphylococcus aureus*) and fungi (*Candida albicans*). A facile synthesis of highly stable AgNPs was reported using a biopolymer, xylan, to reduce and stabilize the agent (Harish et al. 2015). The synthesized AgNPs showed excellent free radical scavenging activity.

In spite of the voluminous reports on biological syntheses of silver nanoparticles, information on the composition of capping agents, protein corona of plant extract-mediated synthesis, and their influence on the properties of AgNPs is scanty. In this direction, de Barros et al. (2018) utilized orange (*Citrus sinensis*) waste as a source of an extract and elucidated the protein corona composition, and also as a starting material for hesperidin and nanocellulose extraction used for the biobased synthesis of AgNPs, which has bactericidal activity against *Xanthomonas axonopodis* pv. *citri* (*Xac*), which causes citric canker in oranges. Cacao contains oxalic acid, a powerful reducing agent, which has been used for its medicinal benefits. Chowdhury et al. (2016) hypothesized that oxalic acid present in cacao extract could reduce precursor silver nitrate to produce AgNPs.

Patra et al. (2019) used an aqueous extract of the outer peel of *Pisum sativum* for the synthesis of AgNPs under different lighting standard conditions. They explored their antibacterial, cytotoxicity, antidiabetic, and antioxidant activities. The wide usage of AgNPs in an array of consumer products consistently results in their release into the wastewater. Cao et al. (2019) demonstrated the pollutant removal (TN and TP) effect of AgNPs in constructed wetlands with different plants *Arundo donax* and *Cyperus alternifolius* and the spatial distribution of silver.

Green synthesis of silver nanoparticles is environmentally viable due to their low cost and safe to nature. Extract of coconut (*Cocos nucifera*) shell was used to synthesize AgNPs, for their antibacterial activity against selected pathogens *Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella typhimurium* (Sinsinwar et al. 2018). Food waste and grape pomace might be used for more environmentally friendly processes to synthesize nanomaterials as they are excellent sources of bioactive compounds. An eco-friendly, quick, one-pot synthetic route has been used by González-Ballesteros et al. (2018) to deal with the potential of *Vitis vinifera* grape pomace in obtaining gold (35 nm) and silver (43 nm) nanoparticles. The functional groups of biomolecules present in grape pomace extract were characterized by FTIR which indicated the involvement of biomolecules in the reducing and stabilization process. Green chemistry based on Kinnow (citrus) peel extract as a reducing and capping agent used for the synthesis of AgNPs (17–27 nm) has been presented by Naz et al. (2017), which can be a useful tool in waste management.

Perveen et al. (2018) have demonstrated the extracellular synthesis of spherical silver nanoparticles (3 to 10 nm) from lychee fruit waste (peel) by reduction and stabilization. Nasar et al. (2019) studied an environmentally viable and economically viable method for synthesizing silver nanoparticles via *Ephedra procera* C. A. Mey mediation. The silver nanoparticles are potential cytotoxic, antimicrobial, and antioxidant agents, and conjugation with selected antibiotics (amoxicillin, cefixime, and streptomycin) with carboxyl, hydroxyl, and alkanes groups are useful as antibacterial bullets against both Gram-positive and Gram-negative bacteria. Lee et al. (2019) have demonstrated biosynthesis of AgNPs using a waste material *Garcinia mangostana* (GM) fruit peel extract and its potential to be used as a potent anticancer drug nanocarrier.

Two natural sources, including cochineal dye with the principle-carminic acid and pomegranate peel extract, were employed to synthesize very dense and fine Ag nanoparticles (15–40 nm). The presence of carminate molecules around the silver atoms prevents the initial nuclei from agglomeration and does not provide enough steric hindrance to prevent the formed nanoparticles from coagulation (Goudarzi et al. 2016). Usually, the extract of the natural product is

used as a reducing agent for Ag nanostructure formation. Antioxidant agents such as phenols, ellagic tannins, gallic, and ellagic acid esters available in pomegranate peel extract were mainly responsible for reducing the silver salt. AgNPs (109.97 nm) photosynthesized by utilizing the aqueous extract of watermelon rind were tested for their antibacterial, anticandidal, and antioxidant activities (Patra et al. 2016). Biocidal AgNPs (40–150 nm) were synthesized using the leaf extracts of subtropical plants *Mangifera indica* (mango), *Eucalyptus teriticornis* (eucalyptus), *Carica papaya* (papaya), and *Musa paradisiaca* (banana) (Mahanty et al. 2013). Banana peel extract contains lignin, cellulose, hemicellulose, and pectin, which are natural reducing agents. Phytosynthesized AgNPs can be used as an alternative to antibiotics, and other biocides as an economically and environmentally viable therapeutic agent against *Aeromonas hydrophila* stimulated diseases in fish.

Other metallic and non-metallic nanoparticles

Agricultural waste materials used in the synthesis of other metallic and non-metallic nanoparticles and their applications in the mitigation of stresses of abiotic and biotic nature are given in Table 2. Ahmad et al. (2019) highlighted the use of the bio-waste extract of *Trapa natans* for rapid, sustainable, and cost-effective biosynthesis of silver (15 nm)

and gold (25 nm) NPs and bimetallic Au-AgNP composites (26–90 nm). Recently, the biological synthesis of selenium NPs is gaining popularity due to their less toxicity, abundantly available source, and pharmacological importance (Pelyhe and Mézes 2013). Biomaterial-derived synthesis used microbes such as bacteria and fungi, with a few from plant origin. Chemotherapeutic nanoscale Se (20–50 nm) was prepared from *Spirulina polysaccharides* by the solution phase method (Yang et al. 2012). Among plants, details of nanoscale Se synthesis were reported using *Vitis vinifera* (raisin) fruit (Sharma et al. 2014). Biologically synthesized nanoscale Se opens options to produce ecologically viable pharmacological additives.

Mangosteen (*Garcinia mangostana*) pericarp waste extract as a reducing and stabilizing agent was used to synthesize Au and AgNPs by a green strategy (Park et al. 2017). The study indicated that GM-AuNPs could be used as drug delivery carriers for biomedical and pharmaceutical applications without significant cytotoxicity. Phytochemical and FTIR spectral analyses indicated that the hydroxyl groups of carbohydrates, glycosides, flavonoids, and phenolic compounds most likely cause the reduction of precursors gold or silver salts to their respective NPs. Francis et al. (2017) have demonstrated rapid microwave-assisted Au and AgNP synthesis derived by aqueous leaf extract of *Mussaenda glabrata* and their antibacterial and pollutant degradation

Table 2 Agricultural waste materials (field/horticultural crops and plantations/tree) used in synthesis of other metallic and non-metallic nanoparticles and their applications in mitigation of abiotic and biotic stresses

Nanostructured material	Waste/material used	Supplemented with	Function	References
Silver ions	Precursor silver nitrate	Zeolite	Ammonia removal; bactericidal	Krishnani et al. (2012)
Silver and gold	Grape pomace (<i>Vitis vinifera</i>)	Biomolecules		González-Ballesteros et al. (2018)
Conducting polymers and nanowire	Polypyrrol Polyaniline	Conducting polymers and Pd thin films	Cr(VI) detoxification Bactericidal	Krishnani et al. (2014)
Silver ions	–	Elastin like biopolymer	Bactericidal activity	Krishnani et al. (2012)
Ag and Au	Mangosteen pericarp waste extract	Ag and Au NPs	Pharmaceutical; biomedical	Park et al. (2017)
Se NPs	<i>Vitis vinifera</i>	Raisin fruit	Pharmacological	Sharma et al. (2014)
ZnO nanoparticles	Goat	Slaughter waste	Controlling pollution	Jha and Prasad (2016)
Pd/CuO Cu NPs	<i>Theobroma cacao</i> <i>Euphorbia esula</i>	Seeds extract	Catalytic activity, Reduction of 4-nitrophenol	Nasrollahzadeh et al. (2015)
Hydroxyapatite nanoparticles	Cow wastes	Wasted bones	Biomedical	Amna (2018)
Fe ₃ O ₄	<i>Vitis vinifera</i>	Core shell Fe ₃ O ₄	Antibacterial activity	Venkateswarlu et al. (2015)
ZnO	<i>Solanum nigrum</i>	Leaf extract	Antibacterial activity	Ramesh et al. (2015)
ZnO	<i>Moringa oleifera</i> <i>Tamarindus indica</i>	Leaf extract	Antibacterial activity	Elumalai et al. (2015a, b)
ZnO	<i>Physalis alkekengi</i>	Shoots	Ion remediation, metals recycling	Qu et al. (2011)
Ag and Au	Cashew	Nut shell, nanometallic dispersions	Antibacterial activity against fish pathogens	Velmurugan et al. (2014)

activities. Biomolecule components having different functional groups in leaf extract, as confirmed by FTIR were responsible for its high potency to perform the reduction process.

Many kinds of solid materials that contain carbon can potentially be used without purification as the feedstocks for the synthesis of high-quality graphene. Akhavan et al. (2014) reported that high-quality graphene oxide and reduced graphene oxide sheets can be synthesized by carbonizing various carbonaceous natural as well as industrial wastes including vegetative (fruit wastes, bagasse, and wood), animals (cow dung, and bone), semi-industrial (newspaper), and industrial origins via imperfect burning at 400–500 °C. The quality of the synthesized graphene oxide and reduced graphene oxide were reported to be the same when compared to graphene sheets obtained from highly pure graphite. Likewise, graphene can be synthesized from agricultural wastes like cricket legs and coconut shells through the chemical vapor deposition method (Ruaysap et al. 2022). Faghiri and Ghorbani (2020) documented that graphene oxide can be synthesized using sugar beet bagasse as a carbon source and can be applied as a stabilizer of silver nanoparticles. They have successfully employed the synthesized graphene oxide nanosheets for more precise and colorimetric detection of Hg^{2+} ions in the environmental water sample. Ruan et al. (2011) developed a cost-effective and inexpensive method for the development of high-quality graphene using low or negatively valued raw C-containing materials such as food (cookie and chocolate), waste (grass, plastic, dog feces), and insect-derived under vacuum. These initiatives bring innovative solutions for the recycling of carbon from impure bioresources.

Synthesis of nanoparticles using animal and fisheries wastes

Various plant materials as well as microorganisms have been reported to synthesize nanomaterials. However, animal materials and their metabolites are rarely used for the biosynthesis of nanoparticles, despite the fact that biomolecules of animal wastes can serve as reducing and capping agents. A significant portion of animal meat production generates waste while producing meat, the quantity of which is staggering. Only about 68–72% of a chicken, 78% of a turkey, 52% of sheep or goats, 60–62% of a pig, and 50–54% of a cow end up as meat for human consumption, and the remainder of each animal becomes waste after processing (Jha and Prasad 2016). Like most food industries, fish processing generates wastes such as carcasses, viscera, skin, and heads. Nearly 63.6 million metric tons of fish waste would be generated globally if about 45% of the live fish weight is considered a waste material (Denham et al. 2015).

Silver nanoparticles

Agricultural materials originated from animal and fisheries wastes used in the synthesis of AgNPs and their applications to alleviate abiotic and biotic stresses are presented in Table 3. Kumar et al. (2017a, b, c; 2018a, b, c, d, e, f, g; 2019) have used green synthesis of AgNPs from fish waste to mitigate multiple abiotic stresses in fish. Jha and Prasad (2014) have reported using the discarded fish gut of *Labeo rohita* to synthesize silver nanoparticles (8–40 nm). Sinha et al. (2014) have developed a cleaner, greener, economically, and environmentally viable irradiation technique for generating self-assembled AgNPs using the aqueous extract of the waste fish scales. Gelatin as a reducing and stabilization agent can form gelatin-AgNP colloidal dispersion dispensing with external reducing agents. The eggshells of *Anas platyrhynchos* are utilized as a reducing and stabilizing agent for the synthesis of AgNPs (6–26 nm) and gold-silver core-shell nanoparticles (9–18 nm) using a greener, environmentally and economically viable way (Sinha and Ahmaruzzaman, 2015a, b).

A large number of animal waste products found in the environment constitute a nuisance. Employing these materials in the green synthesis of the nanoparticles may assist in turning waste into wealth. Animal fur, chicken feathers, and hairs are waste that contains high-quality protein, hard to be degraded. Akintayo et al. (2020) explored animal fur extract-derived biogenic synthesis of AgNPs in the size range of 11.67–31.47 nm, which was found to have high potential as an antioxidant, anticoagulant, and thrombolytic agent.

Other metallic and non-metallic nanoparticles

Agricultural materials originated from animal and fisheries wastes used in the synthesis of other metallic and non-metallic nanoparticles and their applications in the mitigation of stresses of abiotic and biotic nature are given in Table 4. Ahn et al. (2018a) have developed a green synthetic method of anti-tumorigenic and anti-inflammatory Au NPs using the extract of jellyfish sea wastes as a reducing agent. Skate (*Dipturus chilensis*) cartilage extract was utilized as a green reducing agent by Ahn et al. (2018b) for the synthesis of spherical AuNPs with an average size of 16.7 ± 0.2 nm, which can act as drugs or bioactive molecule delivery vehicles. A greener and more innovative method for producing gold and gold-silver core-shell nanostructures has been developed using aqueous fish scales extract of the *Labeo rohita* (Sinha and Ahmaruzzaman 2015a, b). This strategy not only depicted the dual functional ability of the fish scale extract as reducing and stabilizing agents but also eliminated hazardous chemicals/solvents and harsh reducing and stabilizing agents.

Table 3 Aquatic plants/animal and fisheries waste materials used in synthesis of silver nanoparticles and their applications in mitigation of abiotic and biotic stresses

Waste/material used	Capping and stabilizing supplementing material	Function	References
Aquatic plants			
<i>Enteromorpha compressa</i>	Seaweed	Antimicrobial and anticancerous	Ramkumar et al. (2017)
<i>Arundo donax</i> and <i>Cyperus alternifolius</i>	Macrophytes	TN and TP removals	Cao et al. (2019)
<i>Ziziphus jujube</i>	Aqueous extract	Catalytic activity towards reduction of anthropogenic pollutant 4-nitrophenol and Methylene Blue; antimicrobial activity	Gavade et al. (2015)
Animal wastes			
Animal waste	Blood serum	Nanomedicine	Kakakhel et al. (2021)
<i>Anas platyrhynchos</i>	Duck eggshell	removal of toxic and hazardous dyes from aqueous phase	Sinha and Ahmaruzzaman (2015a, b)
Goat waste	Fur extract	Antioxidant, anticoagulant, and thrombolytic agent	Akintayo et al. (2020)
Animal wastes materials	Cobwebs and paper wasp nets	Antibacterial activity	Lateef et al. (2016a, 2016b)
Cockroach	Wings	Insecticidal activity	Khatami et al. (2019)
Cow	Milk	Antimicrobial against phytopathogens	Lee et al. (2013)
Biogenic synthesis of AgNPs using fisheries wastes			
<i>Channa striatus</i>	Fish gill extract, fish feed formulated with AgNPs	Mitigation of abiotic stresses in fish	Kumar et al. (2018c, d)
Fish wastes	Aqueous extract of the fish scales	Reduction of aromatic nitro compounds	Sinha et al. (2014)
<i>Labeo rohita</i>	Gut	Disease control	Jha and Prasad (2014)

A simple environment-friendly protocol, utilizing goat guts and other tissue and organ wastes, has been employed in ZnO nanoparticle (3–11 nm) synthesis. Agricultural waste—eggshells, which are mostly generated from typical households, restaurants, and bakeries—has garnered attention due to their major component of pure calcium carbonate with low porosity. Nanocalcium oxide (Habte et al. 2019) and magnetic CuFe_2O_4 nanomaterials (Zhang et al. 2021) with multifunctional properties such as catalytic and antibacterial functions that have an application in industrial water treatment can be synthesized from a waste egg shell by the sol–gel method.

The fish biowaste constitutes value-added products such as chitin, collagen, bioactive peptides, pigments, and gelatin. Carbon dots and nanocarbons can be synthesized using chitosan as a precursor (Maschmeyer et al. 2020). Reticulated chitosan micro/nanoparticles with an average diameter of 100 nm were synthesized by ionic gelation of chitosan prepared from shrimp shells using tripolyphosphate (Dima et al. 2015), which was further used for complexing stable Cr(VI) anions due to adsorption onto protonated groups in chitosan particles and with the reduction of toxic hexavalent Cr to less toxic trivalent Cr from the solution.

Seafood processing generates a considerable quantity of solid and liquid wastes. There is a great need for a sustainable strategy to minimize environmental pollution and develop products of commercial interest from seafood processing wastes. Crab shells are one of the most common wastes generated by the seafood industry. Bhattacharjee et al. (2019) have synthesized an ultra-fine/ultra-crystalline biomaterial—apatite powder with an average crystallite size of 24.4 nm and particle size of 100–300 nm using crab shells from seafood wastes by an environmentally and economically viable approach. Energy-dispersive X-ray spectroscopy indicated calcium, magnesium, phosphorous, and oxygen as significant elements in the apatite constituents.

Carbon-based nanomaterials are nanostructured cages and are increasingly being used in electronics, energy conversion and storage, catalysis, and biomedicine. Waste materials such as eggshell, fish scales, and shrimp waste are natural sources of useful biopolymers and minerals, which may be used for synthesizing nanoparticles of calcium oxide, calcium carbonate, calcium hydroxide, collagen, chitin, chitosan, and hydroxyapatite (Yadav et al. 2022). Xin et al. (2022) have reported a novel preparation of ultra-bright

Table 4 Agricultural waste (animal and fish) materials used in synthesis of other metallic and non-metallic nanoparticles and their applications in mitigation of abiotic and biotic stresses

Nanostructured material	Waste/material used	Supplemented with	Function	References
Zinc	Fish waste	Fish feed formulated with ZnNPs	Mitigation of multiple abiotic stresses	Kumar et al. (2017b, c, 2018e, f, g, 2019)
Selenium	Fish waste	Fish feed formulated with SeNPs		Kumar et al. (2017a, 2018a, b)
Ag and Au NPs	<i>Mussaenda glabrata</i>	Aqueous leaf extract	Antibacterial dye and 4-nitrophenol degradation	Francis et al. (2017)
Nano-selenium	Spirulina	Polysaccharides	Chemotherapeutic agent	Yang et al. (2012)
Ag and Au	<i>Trapa natans</i>	Bio-waste extract, Au-AgNP composites	Biomedical	Ahmad et al. (2019)
Apatite powder/nanoparticles	Crab	Shells	Drug delivery	Bhattacharjee et al. (2019)
Au NPs	<i>Nemopilema nomurai</i> and <i>Dipturus chilensis</i>	Jellyfish extract and yellow-nose Skate cartilage	Drug delivery: Antitumor and anti-inflammatory and antioxidant activities	Ahn et al. (2018a, b)
Micro/nanoparticles of chitosan	Shrimp shells	Micro/nanoparticles of chitosan	Cr(VI) detoxification	Dima et al. (2015)
Ag and Au	<i>Anas platyrhynchos</i> and fish	Egg shell and fish scales	Removal of hazardous dyes	Sinha and Ahmaruzzaman (2015a)
Ag and Au	<i>Labeo rohita</i>	Fish scales extract, Au and Au–Ag core shell nanostructures		Sinha and Ahmaruzzaman (2015b)
Magnetic CuFe ₂ O ₄ nano-materials	Egg shell	Waste membrane	Adsorptive, catalytic, antibacterial for water remediation	Zhang et al. (2021)
Carbon nano-onions (CNO)	Fish wastes	Fish scales	Catalysis, and biomedical diagnostics	Xin et al. (2022)

carbon nano-onions via one-step microwave pyrolysis of fish scale waste within seconds.

The efficiency of the NPs as photocatalysts is a promising application for removing hazardous dyes from industrial effluents. Amna (2018) have used a facile technique of using the calcination of waste cow bones to synthesize hydroxyapatite NPs without the need for other chemicals or compounds. Hydroxyapatite possesses excellent biocompatibility, osteoconductivity, and non-immunogenic characteristics and is used frequently for diverse biomedical applications.

The use of animal materials including cobwebs (Lateef et al. 2016a), paper wasp nets (Lateef et al. 2016b), cockroach wings (Khatami et al. 2019), bees' honey (Balasooriya et al. 2017), and cow milk (Lee et al. 2013) have been reported to mediate the green synthesis of gold, silver, carbon, platinum, and palladium nanoparticles. The proteins present in these biological materials act as both stabilizing and reducing agents as well as a precursor in nanoparticle synthesis. The physicochemical features of noble Pd NPs include great thermal and chemical stability, and remarkable photocatalytic, electrical, and optical properties (Phan et al. 2019), with a wide range of applications in organic

coupling synthesis, hydrogen storage, fuel cells, sensors, and catalysis.

Microbes-derived synthesis of nanoparticles

Among microbial sources, *Klebsiella pneumoniae* bacteria were used by Fesharaki et al. (2010) for the synthesis of 245-nm-sized Se nanoparticles from selenium chloride as a precursor. Singh et al. (2014a, b) synthesized nano-Se using *Bacillus* sp. JAPSK2 and selenium chloride as a precursor. Srivastava and Mukhopadhyay (2013) described selenium nanostructures' biosynthesis from selenium oxyanions by using the bacteria *Zooglea ramigera*. Bahrami-Teimoori et al. (2019) has demonstrated that both natural sources; industrial wastewater-acclimated *Bacillus* sp. and wild-growing *Amaranthus* sp. can create biologically active AgNPs efficiently. The AgNPs would be of keen interest in circumventing current antibiotic resistance. Microalgae serves as a living cell factory for efficient green synthesis of nanoparticles due to their unique characteristics of higher growth rate, minimum energy input, and the presence of enzymes and pigments, which act as reducing and capping agents (Khan et al. 2022). AgNPs can be synthesized from

an aqueous extract of marine algae *Sargassum myriocystum*. Singh et al. (2014a, b) described a simple, economically viable, and unexplored method of using cell extracts of the cyanobacterium *Anabaena doliolum* for the “green” synthesis of AgNPs as a potential antibacterial and antitumor agent.

Valorization of biologically synthesized nanoparticles for applications in fisheries and animal husbandry

In the last decade, nanomedicine-based nanotechnology has emerged as the frontier in the therapeutic and pharmaceutical fields. Nanotechnology has paved the way to open up new perspectives to analyze biomolecules, proteins, or cells, targeted drug delivery, development of non-viral vectors for gene therapy, clinical diagnosis, a transport vehicle for DNA, and disease therapeutics. In modern agriculture, agri-food nanotechnology is one of the essential tools, which is anticipated to become a driving economic force in the near future. Rabiee et al. (2022) synthesized CaZnO-based nanoghosts using a high-gravity technique based on the use of *Rosmarinus officinalis* leaf extract as the templating agent and developed a cost-effective highly selective method to detect SARS-CoV-2 in different environments. The detection and evaluation of trace concentrations of antigens and gene-related sequences remain challenging, making different pathogens stronger. Recently, graphene-based nanomaterials have effectively been utilized in the prevention, detection, treatment, medication, and health effect issues due to their large surface area, special physicochemical and efficient thermal and electrical properties, easy functionalization, C-based chemical purity, and more importantly antimicrobial activities (Ebrahimi and Akhavan 2022; Ebrahimi et al. 2022).

The sustainability and protection of agriculturally produced foods, including crops for human consumption and animal feeding, are the main agri-food themes, which not only provide new agrochemical agents and novel delivery mechanisms to improve crop productivity but also boost agricultural production, and input use efficiency (Sekhon 2014). Recently, zeolite, a group of minerals, has emerged as having considerable potential in a wide variety of agricultural processes. Recent advances in zeolite synthesis have offered a new group of materials such as yolk/core–shell materials with more unusual and sophisticated morphologies or architectures/hierarchical structures in which the average diffusion path is reduced significantly and also nanoparticles are protected against poisoning or sintering by a thin zeolite shell. As compared to nanometric intrinsic cavities of zeolite frameworks, a large internal void is available for chemical reactions. Such catalysts, in which the permeability of the shell essentially governs the reaction can be considered as

nanoreactors. Zeolites are microporous crystalline solids hydrated aluminosilicates of alkali crystals and earth metals that possess infinite and three-dimensional crystal structures. Such inter-crystalline and intra-crystalline mesopore systems have been widely used to encapsulate cations, complexes, and metals. Because of the unique dehydration-rehydration, adsorption, thermal stability, water retentivity, a cage-like structure consisting of SiO_4 and AlO_4 tetrahedra joined by shared oxygen atoms and ion-exchange properties of natural zeolites, they are used extensively as amendments in industries, agriculture, aquaculture, and water treatment for many years. The presence of exchangeable cations balances the negative charges of the AlO_4 units, and cations Ca, Mg, Na, K, and Fe, which can be readily displaced by heavy metals and ammonium ions. The pronounced selectivity of zeolites for large cations, such as ammonium and potassium, can also be exploited to prepare chemical fertilizers that improve the soils' nutrient-retention ability by promoting a slower release of these elements for uptake by plants. Microporous cavities and mesoporous channels of zeolite frameworks can particularly be adapted for supporting nanoparticles. In addition, modifications of the surface and pores of zeolites make them attractive candidates for various applications. The value addition of zeolites through nanotechnological interventions can be explored to mitigate abiotic and biotic stresses in aquaculture and their potential applications in agriculture.

Silica is found in agricultural plant ash residues of paddy straw, wheat straw, bagasse, bamboo leaves, and coconut shell in the range of 38 to 93% along with metal and alkali oxides such as Fe_2O_3 , Al_2O_3 , ZnO, MnO, CuO, TiO_2 , Sr_2O_3 , K_2O , MgO, CaO, Na_2O , and others. Synthesis of biogenic silica from cereal crop waste has been attempted due to the high silica content of cereal crops and residues (Sarkar et al. 2015). Thermal, chemical, and biological treatments can be utilized to produce SiNPs from agricultural wastes.

Mitigation of abiotic stresses using biologically synthesized nanoparticles and their valorized products

The applications of nanometals in crop plants have been promising seen. However, their applications in aquaculture and livestock are relatively new. They have potential applications in fisheries and aquaculture in terms of water quality improvement, nutrition, drug delivery, disease diagnosis, and health management.

Fisheries

The comparative evaluation of extremely sophisticated nanotechnology based on metal-containing engineered nanomaterials (ENMs) with conventional process engineering

proposes a new prospectus in technological developments for various applications including superior water and wastewater technology processes. These materials can be transformed during wastewater treatment and ultimately enter terrestrial ecosystems via agriculturally applied biosolids (Lewis et al. 2017). Water contamination is a serious threat to public health. Aquatic pollutants of chemical and microbial origin create a significant threat to water quality when the safety standards are not followed. Nanotechnology provided nanocatalysts such as ZnO, TiO₂, and WO₃ for the degradation of anthropogenic water pollutants (Sarkar et al. 2017) including rhodamine B and methyl orange effectively from the aquatic environment and wastewater sewages of dye industries. The synthesized nanoparticles' catalytic capacities were studied to reduce 4-nitrophenol (Francis et al. 2017). The hydrophobic and electrostatic interactions between the micelle and the substrate are responsible for the nanoparticle catalytic activity in the micelle to reduce aromatic nitro compounds.

Kumar et al. (2018c, d) have successfully demonstrated that dietary AgNPs with a low concentration (0.5 mg/kg diet) as the growth promotor significantly improved the growth performance, immunological status, and antioxidative status of *Channa striatus*. Also, the AgNPs reduced other cellular stress and finally protected *C. striatus* against the challenge of *Aeromonas veronii* biovar *sobria* and concurrent exposure to Pb and high temperature. Kumar et al. (2017a, 2018a, b) have demonstrated that Se NPs at a 1 mg/kg diet have protected fish from abiotic and biotic stresses, as evidenced by the enhanced growth performance, antioxidative defense, and immune rescuing ability of the fish.

Experiments were carried out by Kumar et al. (2017b, 2018e) to investigate the effects of concurrent exposure to stresses elicited by lead, and elevated temperature and evaluation of zinc nanoparticles counteract these stresses in *Pangasius hypophthalmus*. Results concluded that dietary zinc nanoparticles (Zn-NPs) at 10 and 20 mg/kg diet could be more effective in enhancing the thermal tolerance and other biochemical attributes such as neurotransmitter enzyme acetylcholine esterase activities and oxidative stress and lipid peroxidation (LPO) in the liver, gill, and brain of *P. hypophthalmus* were noticeably reduced in the concurrent exposure to Pb and high temperature. However, further work on the elucidation of the mode of action of ZnNPs in enhancing thermal tolerance in fish could be of immense use in aquaculture.

Krishnani et al. (2014) have successfully demonstrated electrochemically synthesized polyaniline, polypyrrole conducting polymers, and nanowires and their Pd decorated thin films for reduction of toxic hexavalent chromium Cr(VI) into less toxic Cr(III) and its subsequent adsorption onto the polymer. Based on this research finding, polyaniline conducting polymer is recommended for sensor applications for Cr(VI)

detection at low pH. They reported a decrease in percent Cr(VI) reduction with an increase in pH from 1.8 to 6.8 and with initial Cr(VI) concentration ranging from 2.5 to 10 mg/L.

Intensive aquaculture results in a rise in nutrient concentration in the water bodies. High nutrient concentrations lead to severe eutrophication of freshwater, brackish water, and marine waters. Nitrogenous toxicants such as ammonia and nitrite are abiotic stresses in aquaculture. Intensive shrimp aquaculture is associated with elevated concentrations of total ammoniacal nitrogen (TAN) due to high shrimp excretion and feed loading (Shan and Obbard 2001). TAN is the major end-product of protein catabolism. A higher concentration of TAN and other nutrients can adversely affect productivity and aquaculture waters by causing eutrophication and stress, unfavorable to the animals but favorable to the pathogens (Krishnani et al. 1997).

Animal husbandry

Like the agricultural and aquaculture industries, livestock and poultry are the largest industries in the food sector due to the global demand for meat. However, they have also been threatened by environmental parameters such as wind speed, relative humidity, ambient temperature, and solar radiation interact to form heat stress, causing diseases that affect the breeding and growth of livestock and poultry (De Silva et al. 2021). Heat stress can potentially restrict cattle production, affect their reproduction, milk quality and quantity, feed availability, and reduce dry matter intake. Heat stress causes increased respiration rate and saliva production and is responsible for the reproductive disruption. The conception rate decreased beyond temperature extremes and resulted in low fertility in cows, inseminated during the summer months (Madhusoodan et al. 2019). Abiotic stressors, including pollution, climate change, and consequent oxidative stress, can damage cells as they continue to release reactive oxygen species. These reactive oxygen species are extremely harmful to cell biomolecules like protein, lipid, and DNA.

The use of selenium nanoparticles is recommended by Rayman (2005) to reduce oxidative stress in animals. Selenium nanoparticles also possess anticarcinogenic properties and aid in thyroid metabolism, proper muscle functioning, and reproduction. The administration of nanoselenium helps in increasing the productivity of stress-ridden livestock (Sarkar et al. 2015). When supplemented with broiler chicken's diet, copper oxide nanoparticles tend to reduce the heat stress-induced responses such as malonaldehyde concentration in the liver, and hepatic tissue degeneration and enhance glutathione peroxidase, superoxide dismutase, and catalase enzyme activity. Recommended supplementation of CuO NP could minimize the negative consequences of heat

stress or elevated temperature during the summer months (El-Kassas et al. 2020).

Dietary supplementation of curcumin (native and solid nanoparticle form) in heat-stressed rabbits acts as natural antioxidants and normalizes physiological functions. The result demonstrated that dietary inclusion of curcumin NPs at 2.5 mg/kg positively affects the final body weight, feed conversion ratio, and survival. It also showed a significant increase in antioxidant activity, total protein retention, and immunological performances. It resulted in a reduced concentration of cholesterol, low-density lipoproteins, triglycerides, urea, and malonaldehyde (El-Ratel et al. 2020).

Mitigation of biotic stresses using biologically synthesized nanoparticles and their valorized products

Fisheries

Aquaculture is one of the most important economies in many countries. However, biotic stresses caused by bacterial, viral, fungal, and parasitic origins are emerging constraints to aquaculture production. Disease-causing and the most common resistant bacterial strains are *Aeromonas salmonicida*, *Photobacterium damsela*, *Yersinia ruckeri*, *Listeria* sp., *Vibrio* sp., *Pseudomonas* sp., and *Edwardsiella* sp., which adversely affect both freshwater and saltwater fish as well as shellfish species and aquaculture productivity. During the past decade, the shrimp production level has been increased and also accompanied by various diseases. Vibriosis outbreaks are a common problem in shrimp aquaculture worldwide, predominantly in India, creating an economic loss due to mass mortalities in hatcheries and grow ponds of shrimp. The development of antibiotic resistance in aquatic microbes has renewed a great interest in alternative methods of preventing and controlling diseases. Recently, production demands on the aquaculture industry have been centered around using antibiotics due to increased incidences of antibiotic-resistant bacteria with new avenues to use nanoparticles in the fish feed. Nanostructured materials not only have potential applications in controlling human, animal, and fish pathogens but also have comprehensive advantages in terms of holding the assurance for civilized protection of farmed fish against disease-causing pathogens (Dar et al. 2019).

Vibrionaceae is a bi-folded drug-resistant emerging pathogen active in various aquaculture sectors, especially in shrimp culture worldwide. *V. parahaemolyticus* is the most dreadful viral outbreak in shrimp culture. However, *Vibrio* species such as *V. harveyi*, *V. parahaemolyticus*, *V. vulnificus*, and *V. cholerae* are mostly opportunistic pathogens in aquatic environments (Karunasagar et al. 1994). Vibriosis has caused mass mortality of the shrimp reared in hatcheries and grow-out farms (de la Pena et al. 1993;

Haldar et al. 2010). The presence of *V. parahaemolyticus* and *V. cholerae* in shrimp is a human health concern since these bacteria can cause acute gastroenteritis (Spite et al. 1978). Chemical control of *Vibrio* contamination is difficult (Baticados et al. 1990). There is a need to find new types of safe and cost-effective materials to eliminate and control the spread of such pathogens in foods or food processing environments. Red algae *Portieria hornemannii* was investigated to synthesize silver nanoparticles, which were found to be effective against the fish pathogens such as *Vibrio harveyi*, *V. parahaemolyticus*, *V. alginolyticus*, and *V. anguillarum* (Fatima et al. 2019). This approach can be used as an alternative to commercially available antibiotics in the treatment of fish diseases. Sarkar et al. (2012) have developed a simple, single-step, environmentally viable, and cost-effective process for the synthesis of bactericidal silver nanoparticles (2–70 nm) using different organs (intestine, gills, and liver) of freshly sacrificed fish—rohu (*Labeo rohita*). With additional chemical intervention, these nanoparticles have applications for controlling fish pathogen *Aeromonas hydrophilla* in aquaculture and related aquatic environments. Elayaraja et al. (2017) bacterial cellulose (BC) membrane produced by *Gluconacetobacter xylinus* in cell suspension was oxidized by TEMPO (2,2,6,6-tetramethylpiperidine-1-oxyl radical) to activate the carboxyl group. AgNP anchored with BC TEMPO was generated to increase vibriocidal activity against the shrimp pathogen *V. parahaemolyticus* and *V. harveyi*.

Ichthyophthirius multifiliis is a widespread and ciliated protozoan ectoparasite of fish. Saleh et al. (2017) have investigated the effects of metal nanoparticles (Au, Zn, and Ag) on the reproduction and infectivity of free-living stages of *I. multifiliis*. They have successfully demonstrated that metal nanoparticles, particularly silver nanoparticles, hold the best promise for developing effective antiprotozoal agents useful in managing ichthyophthiriosis in aquaculture. Swain et al. (2014) have screened several metallic and metal oxide nanoparticles for their antimicrobial activities against a wide range of aquatic microbes (bacterial and fungal agents), including certain freshwater cyanobacteria. They have reported that synthesized copper oxide (CuO), zinc oxide (ZnO), silver (Ag), and silver-doped titanium dioxide (Ag-TiO₂) showed a broad-spectrum antibacterial activity, as they may be good candidates for aquaculture use. On the contrary, nanoparticles like Zn and ZnO showed antifungal activity against fungi like *Penicillium* and *Mucor* species.

Akhavan and Ghaderi (2009) investigated the antibacterial activity of graphene oxide nanosheets, immobilized on anatase titanium oxide thin film against *E. coli* under solar light irradiation, which can be attributed to UV-assisted photocatalytic reduction of immobilized graphene oxide nanosheets acting as the sensitizer of the TiO₂ leading to photoinactivation of bacteria. Further, the photoinactivation

efficiency of graphene oxide nanosheets on TiO₂ thin film is greatly influenced by the photocatalytic reduction of graphene oxide nanosheets, as the increased photocatalytic reduction could improve the antibacterial activity by several folds when compared to annealed graphene oxide-TiO₂ (the bare TiO₂) thin film. The same mechanism (bactericidal activity under solar light irradiation) of Ag-TiO₂ nanomaterial has been reported by Akhavan (2009) and Ag-TiO₂/Ag/a-TiO₂ photocatalyst has been recommended as one of the effective and long-lasting antibacterial nanocomposite materials (Akhavan 2009).

Rapid reduction and stabilization of Ag⁺ ions with different molar concentrations of NaOH have been carried out in silver nitrate solution by the biowaste peel extract of *Pomgranate granatum* (Jasuja et al. 2015). The AgNPs synthesized at 1.5 mM NaOH concentration had shown maximum zone of inhibition in *E. coli*, compared to *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Bacillus subtilis*. Biowaste-assisted nanosynthesis has the potential to be scaled up to meet sustainable green applications (Aswathi et al. 2022).

The white spot syndrome virus (WSSV) is a major viral pathogen in the shrimp aquaculture industry. Ochoa-Meza et al. (2019) have demonstrated that a single dose of silver nanoparticles at 12 ng/mL could enhance the shrimp immune system's response without toxic effects on healthy shrimps with the result of 20% survival of treated infected shrimps, as there was no any histological evidence of damage at this concentration. Moreno (2017) evaluated the survival rate of juvenile white shrimps (*Litopenaeus vannamei*) after the intramuscular injection of different concentrations of AgNPs and polyvinylpyrrolidone (PVP) alone into the organisms with the result of more than 90% of shrimp survival after 96 h for all treatments. They further demonstrated that oxygen consumption rate and total hemocyte count remained unaltered after AgNP injection, reflecting no stress caused. Based on these promising results, they recommended further exploration of the potential use of AgNPs as antiviral agents for the treatment of diseases in aquaculture organisms. AgNPs were formulated into a vaccine to treat WSSV (Rajeshkumar et al. 2009).

Aeromonas hydrophila is a major infectious aquatic pathogen, which has reportedly developed resistance against many of the available antibiotics. This is the causative agent of ulcers, fin-rot, tail-rot, and hemorrhagic septicemia in fish. Mahanty et al. (2013) studied the inhibitory function of silver nanoparticles (AgNPs) against *A. hydrophila* for its possible application in aquaculture as an alternative to antibiotics.

Krishnani et al. (2014) have developed a recombinant elastin-like biopolymer (ELP) composed of a polyhistidine domain with silver and successfully demonstrated its bactericidal activity with a minimum inhibitory concentration

of 37 µg/ml against pathogenic bacteria against *Escherichia coli*, a model test strain for Gram-negative bacteria for antibacterial assays of nanoparticles and *Vibrio harveyi*, an opportunistic pathogen that causes mass mortality in shrimp *Penaeus monodon* reared in coastal aquaculture. This study has an application in formulating artificial protein-based antibacterial in diverse healthcare fields and managing disease in aquaculture.

Tea waste contains polysaccharides, caffeine, and tannic acid which act as reducing and capping agents (Gowda et al. 2022). AgNPs synthesized from tea plants at a concentration of 10 ppm inhibited *Vibrio harveyi* in infected white shrimp (*Fenneropenaeus indicus*) (Vaseeharan et al. 2010). Sivaramasamy et al. (2016) synthesized AgNPs using *Bacillus subtilis* and tested its antibacterial potential on *Vibrio parahaemolyticus* and *Vibrio harveyi* on white leg shrimp. In another study, AgNPs encapsulated with starch were used to treat *Ichthyophthirius multifiliis* and *Aphanomyces invadans* fungal infections in fish species (Barakat et al. 2016; Daniel et al. 2016).

The biological synthesis of nanoselenium paves the way for pharmacologically enriched, naturally stable nanoscale Se with high ecological viability (Sarkar et al. 2015). Such nano-Se mixed with commercial feeds can improve stress resilience and productivity of fish and livestock. Oxidative stress is responsible for reduced productivity in fisheries and livestock. Essential micronutrients play a very important role in combating oxidative stress. Nano Se acts as a potent antioxidant with reduced toxicity. The mechanism behind the role of dietary ZnNPs in enhancing thermal tolerance may be due to their role in repair and protection against damage from cellular stress associated with protein denaturation at elevated and lowered temperatures for controlling the expression of heat shock proteins (Nakano et al. 2002), besides the establishment of homeostasis with increased stimulation of the non-specific defense mechanism (Fraker et al. 2000; Rink 2011).

Increased bacterial resistance to antibiotics is a major challenge for disease management. The investigation of alternative antimicrobials is one of the strategies to limit the development of antibiotic resistance. Silver nanoparticles have emerged as a powerful weapon against antibiotic-resistant microorganisms. Shalaan et al. (2018) have demonstrated the antibacterial properties of silver nanoparticles against *A. salmonicida* infection, which can develop antibacterial agents in aquaculture. AgNPs, possessing good antimicrobial activity, are widely used in many fields. Yang et al. (2016) have demonstrated that the incorporation of AgNPs influences biofilm bacterial communities in the marine environment and subsequently inhibits mussel settlement. Treatment of sepsis fish pathogens using nanosilver marine fungal chitosan could be an alternative as antibiotic synergizers. Francis et al. (2017) have successfully demonstrated that

the synthesized gold and silver nanoparticles are potential inhibitors of pathogenic microorganisms including *Bacillus pumilus*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Aspergillus niger*, and *Penicillium chrysogenum*. Spherical and triangular nanostructures of the silver (2–17 nm) and gold (2–19 nm) nanoparticles were synthesized by Vijayan et al. (2014) using an aqueous extract of the seaweed *Turbinaria conoides*. They evaluated the nanostructures for their antibiofilm forming activity against marine bacteria and found that the synthesized AgNPs were efficient in controlling the bacterial biofilm formation by *E. coli*, followed by *Salmonella* sp., *S. liquefaciens*, and *A. hydrophila*, whereas AuNPs did not show any remarkable antibiofilm activity.

Mahanty et al. (2013) have synthesized silver nanoparticles (AgNPs 10–150 nm) using the leaf extracts of subtropical plants *Mangifera indica* (mango), *Eucalyptus terticornis* (eucalyptus), *Carica papaya* (papaya), and *Musa paradisiaca* (banana) and evaluated the inhibitory function of AgNPs against *Aeromonas hydrophila*. Their study revealed that the papaya leaf extract synthesized AgNPs had maximum antimicrobial activity at 153.6 µg/ml and the eucalyptus leaves extract was the least. Also, the potency of the nanoparticles was enhanced with the decrease in particle size, from 60–150 nm in eucalyptus to 25–40 nm in papaya. Krishnani et al. (2012) investigated the antimicrobial activity of silver ion-exchanged zeolite against *Escherichia coli*, *Vibrio cholerae*, *Vibrio harveyi*, and *Vibrio parahaemolyticus*, and the MIC was found to be 40 µg/ml and 50–60 µg/ml, respectively.

AgNPs as a nanocarrier offers better adsorption of nutraceuticals essential for the growth of fish species. However, the literature on the application of AgNPs in aquaculture nutrition is scanty. Alishahi et al. (2011) reported that fish feed incorporated with chitosan–TPP/vitamin C nanoparticles resulted in better absorption of the nutrient in rainbow trout.

Animal husbandry

Livestock production demands their flocks and herds achieve slaughter size within the shortest possible time to maximize their profitability. Antibiotics are profusely used as feed additives by livestock producers to attain the ideal slaughter size, prevent illness, and accelerate overall growth. While it is conducive from a production viewpoint but at the same time, excessive use of drugs led to a rise in antibiotic-resistant bacteria and meat contamination. *Pseudomonas aeruginosa*, *Escherichia coli*, *Salmonella enterica*, *Staphylococcus aureus*, *Streptococcus agalactiae*, and *Klebsiella pneumoniae* are foodborne pathogens that adversely affect livestock including cows, goats, sheep, and pigs (El-gohary et al. 2020). Nanoparticles have been identified as solutions

to such restrictions without influencing antibiotic resistance in microbes (Hill and Julang 2017). In this aspect, the adjuvant mechanism of aluminum hydroxide nanoparticles was investigated by Tang et al. (2008) and their result demonstrated that it could initiate a cellular and humoral immune response against Newcastle disease in chickens than conventional aluminum adjuvant.

Metal nanoparticles have wide utilization in agriculture and the veterinary field as a disease treatment agent. Examples of such nanoparticles are highlighted as follows: colloid nanosilver particles (silver content 0.05–0.10% by weight) act as a bactericidal agent against mastitis in cows (*Staphylococcus* spp., *Escherichia coli*, and *Streptococcus* spp.); Argovit (a compound of nanosilver and polyvinylpyrrolidone) used as a therapeutic and prophylactic agent in piglets to reduce disease outbreak and mortality; silver, magnesium, and copper oxide NPs were shown to possess high antimicrobial activity against Gram-positive and Gram-negative microorganisms that causes digestive tract diseases and periodontal diseases in horses (Perfileva et al. 2019).

Silver nanoparticles are also used to inhibit the growth of hemorrhagic enteritis, inciting *E. coli* O157: H7 and yeast of bovine mastitis (Hill and Julang 2017). ZnO (zinc oxide) nanoparticles can prevent different fungal and zoonotic diseases in cattle by inhibiting the germination of fungi (*Trichophyton mentagrophyte*, *Microsporum canis*, *Candida albicans*, and *Aspergillus fumigates*) at a dose of 40 mg ZnO/ml (El-Diasty et al. 2013). Nano-zinc oxide and montmorillonite were used as anti-diarrhea agents in piglets (Hu et al. 2012). Supplementation of chitosan nanoparticle-loaded copper increases average feed intake capacity and reduces diarrhea outbreaks (Huang et al. 2015). As domestic swine are severely affected by the African swine fever virus (ASFV) due to no vaccine or proper medication, silver nanoparticles (SNPs) have been identified as novel antiviral agents against the swine viruses. It is observed that the application of SNP solution at 25 ppm in the pig houses can prevent ASFV transmission and act as an antiviral agent against this disease (Dung et al. 2020).

Kalinska et al. (2019) used AgNPs in pure AgNPs and the combination of silver and copper nanoparticle complex (AgCuNP) as strong antibacterial and antifungal agents in dairy and goatery for preventing mastitis caused by pathogenic *Escherichia coli*, *Staphylococcus aureus*, *Enterobacter cloacae*, *Enterococcus faecalis*, *Streptococcus agalactiae*, and *Candida albicans*. Fondevila et al. (2009) supplemented AgNP colloid in the feed for the reduction in coliforms in pig microbiota and an increase in pig growth rate. Poultry faces the challenges of pathogenic infections causing tremendous loss. AgNPs can act as a growth promoter and an effective antibacterial agent in poultry resulting in increased body weight (Sawosz et al. 2009; 2012; Raieszadeh et al. 2013; Chmielowiec-Korzeniowska et al. 2015).

Bacterial and fungal species secrete many chemicals and mycotoxins that contaminate animal feed, which causes major diseases in animal husbandry including dairy, goatery, piggery, and poultry (Kakakhel et al. 2021). The inorganic salts, commonly used as feed additives, exhibit poor bioavailability in animals. Alternatively, metallic NPs including zinc, silver, copper, gold, selenium, and calcium nanoparticles are potential feed additives to enhance the health, performance, and production of livestock, which has the potential to mitigate multiple stresses related to animal health (Michalak et al. 2022; Tatli Seven et al. 2018) as nanominerals supplemented with animal feed act as growth-promoting, immune-stimulating, and antimicrobial agents. Nanomaterials could improve reproduction in poultry, livestock, and fisheries (Swain et al. 2015).

Mitigation of multiple stresses using valorized products

Fisheries

The fish disease is a major stumbling block toward sustainable growth of the fisheries sector. The fisheries sector demands more technical innovation in drug use, disease treatment, nutraceutical delivery for rapid growth promotion, water quality management, and production of tailored fish for suiting better health. Nanotechnology has tremendous potential to revolutionize agriculture and allied sectors, including aquaculture and fisheries. Nanoparticles can serve as the functional unit and act as a delivery vehicle for materials conjugated to their surface or encapsulated within (Hill and Julang 2017). There is an immense opportunity to use the nanoparticles to deliver nutraceuticals in fish feed and nutrigenomics studies. For these multiple-purpose efforts, the importance of nanotechnology and nano delivery of vaccines, nutraceuticals, inducing hormones, growth-promoting anabolics, and drugs open tremendous opportunities including delineation of the possible future application of nano delivery for aquaculture development (Aklakur et al. 2016). Krishnani et al. (2012) successfully demonstrated that silver ion-exchanged zeolite could impact disease and environmental management in shrimp aquaculture.

Changes in the aquatic water body's temperature affect behavior, migration, metabolic processes, growth, reproduction, survival rate, and life span of the fish (Portner 2001) due to their poikilothermic nature. The rise in the temperature and contamination level reduces the thermal tolerance of aquatic animals, including fish. Concurrently, it also altered the antioxidative defense systems through oxidative stress and other cellular metabolic enzymes (Abele and Puntarulo 2004; Portner 2002). Incorporating AgNPs at 0.5 mg/kg in the diet can confer protection to fish against Pb and thermal stress and enhance thermal tolerance of *C. striatus* (Kumar et al.

2018c; 2018d), as the enzymes involved in protein metabolism, carbohydrate metabolism, acetylcholine esterase, and antioxidant activities were normal in fish fed with a 0.5 mg/kg AgNPs supplemented diet. Kumar et al. (2017a, b, c; 2018a, b, c, d, e, f, g, 2019) have developed a novel feed formulation, wherein nano zinc has been demonstrated as an important nanodelivery component in fish feed in enhancing the thermal tolerance and protection against cellular stress in fish exposed to heavy metal-lead and temperature. Also, Kumar et al. (2017a, 2018a, b) have developed a novel feed formulation, wherein nano selenium has successfully been demonstrated as an important nanodelivery component in fish feed in mitigating multiple stresses in fish.

There are many other studies that showed that the application of nanometals has a beneficial effect on fish. Se-yeast and nano-Se showed better growth performance, antioxidant activities, and enhanced fish blunt snout bream meat quality than Na_2SeO at 0.2 mg Se/kg (Liu et al. 2017). With vitamin C300 + Nano Se 0.68 mg/kg, blood physicochemical characteristics Hb, WBC, and RBC count improved, and liver and muscle protein content increased in Mahseer fish juveniles (Khan et al. 2017). SeNP acts more efficiently on growth performance and antioxidant defense system of common carp than organic and inorganic sources of Se (Saffari et al. 2017). Two times more uptake of vitamin C was noticed with nano-encapsulated form in *Solea senegalensis* post-metamorphic larvae, Rotifers *Brachionus plicatilis* (Jimenez-Fernandez et al. 2013). RBCs and hemoglobin levels, immune parameters, bactericidal activity, and myeloperoxidase activity were higher in the FeNP-treated diet in rainbow trout and *Labeo rohita* (Behera et al. 2014). Nanodiet feed-fed fishes showed a gradual increase in weight gain, length gain, and specific growth rate of fish *Catla catla* (Vineela et al. 2017). Izquierdo et al. (2017) have successfully demonstrated that adding Zn, Mn, and Se in the form of nanometals did not enhance growth but improved stress resistance and bone mineralization in seabream larvae. Dietary supplementation with 0.2 mg/kg Se NP showed increased weight gain rate and reduced feed coefficient and offers resistance to hypoxia stress and improves immunity and disease resistance in Chinese mitten crab *Eriocheir sinensis* (Qin et al. 2016). Wang and Li (2011) have demonstrated that the addition of chitosan nanoparticles significantly improved the final weight, daily weight gain, and feed conversion ratio of the fish tilapia (*Oreochromis nilotica*). ZnNP supplementation up to 60 mg/kg showed significantly improved performance in survival, growth, and activities of digestive enzymes (protease, amylase, and lipase) in prawn *Macrobrachium rosenbergii* (Muralisankar et al. 2014). Vitamin E-supplemented diets can exert positive effects on the welfare of chronically stressed rainbow trout subjected to an additional acute stressor (Naderi et al. 2017). The experimental study conducted by Asaikkutti et al. (2016) demonstrated that prawns

fed with a diet supplemented with 3–18 mg Mn-oxide NPs/kg enhanced growth performance, final weight, and FCR.

Nanobioremediation has potential applications in the environmental management of aquaculture systems. Krishnani et al. (2012) have synthesized silver-ion-exchanged-zeolite, which has been recommended as a low-cost material for bactericidal and ammonia removal activities in aquaculture. In another study, nano-chitosan/zeolite composite at 5 g/kg had the potential to enhance growth performance, digestive enzyme activities, and some biochemical parameters in rainbow trout (Sheikhzadeh et al. 2017). The applications of chitosan and chitosan nanoparticles attracted the interest of many researchers in the field of aquaculture, including antioxidant activity, growth enhancement, and immunostimulatory effects (El-Naggar et al. 2022).

Animal husbandry

Sahoo et al. (2014) scrutinized zinc nanoparticles as an immunomodulatory agent to boost immunity in broiler chickens. Administration of Zn nanoparticles at 0.06 ppm can improve the immune response compared to conventional inorganic and organic Zn (Sahoo et al. 2014). Supplemented Zn nanoparticles alter the production of volatile fatty acids and can change the kinetics of rumen fermentation. It has also contributed to improved growth of ruminal microorganisms, microbial protein synthesis, and efficient energy utilization (Zhisheng 2011).

Furthermore, nanotubes implanted under the skin of livestock can provide real-time estradiol concentration in the animal blood (Rajendran 2013). Nanomaterials are also used to design various sensors to study the actual causes of abortion in live stocks. The application of nanoantioxidants improves reproductive or infertility problems in veterinary practice (Swain et al. 2015). Similarly, nanocalcium carbonate can significantly enhance the absorption and utilization rate of calcium in farmed livestock. Vitamin D₃ in the nano-level, when added to the feed of egg-laying hens, showed better performance compared to ordinary vitamin D₃ (Huang et al. 2015).

It has also been noticed that persistent ischemia (deficiency of arterial blood supply to various organs) in livestock can lead to atrophy or necrosis of the affected organ. Therefore, it is crucial to trigger angiogenesis (formation of new blood capillaries from the pre-existing blood channels) in the targeted area without affecting the normal tissue. Zinc oxide nanoflower showed a significant angiogenic property in chick embryos *in vivo* and *in vitro* conditions (Raguvaran et al. 2015).

Metal nanoparticles, liposomes, carbon nanotubes, quantum dots, and nanocomposites can be used in various fields of nanomedicine for improving animal health and production, such as efficient diagnostic and therapeutic tools, drug/nutrient

delivery, animal nutrition, breeding and reproduction, protein, antimicrobial agents, and valuable/feeding additives (Hassan et al. 2020).

Valorization of biologically synthesized nanoparticles for applications in the field and horticultural crops

The importance of nanotechnology in agriculture and relevant industries is well established as it serves as an interdisciplinary technique to resolve various lacks and problems. It has been documented that nanotechnology includes four developmental stages. Stage 1 represents the designing of “passive nanostructures,” capable of deploying the passive properties of the material used. The second stage focuses on developing an “active multitasking nanostructure,” and in the third stage, several nanotools forming a “nanosystem” works in combination to reach a common goal. Finally, the fourth stage represents the era of designing molecular-based nanosystems and leads to atomic and molecular instruments with diversified functions (Elnashaie et al. 2015). The synthesized nanoparticles can be valorized by challenging their structural complexity, and these value-added nanostructured materials are comparatively more versatile.

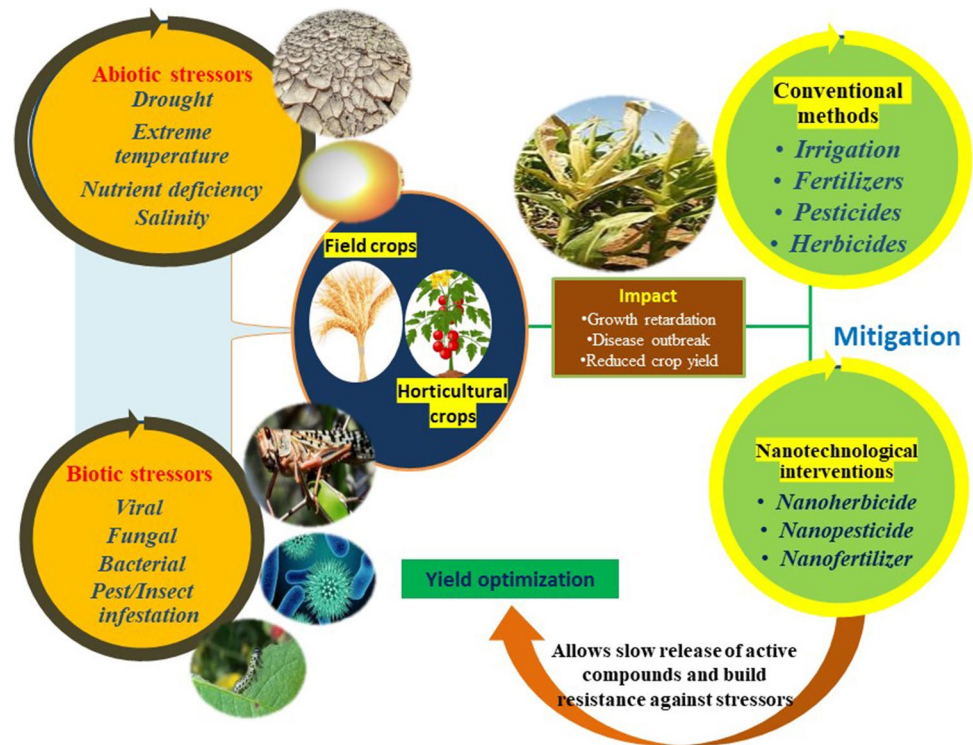
Integration of valorized nanoparticles with existing technologies can revolutionize the agricultural sector and aid in developing new alternatives for disease diagnosis, enhance the nutrient absorption ability of the crops, and withstand unfavorable environmental conditions. It ensures practical storage, processing, as well as the packaging of the products. Sharon et al. (2010) suggested that nanotechnology can solve various crop production issues and postharvest products. Similarly, nanostructured materials are available commercially, enhancing herbicides and pesticides’ efficiency, thus reducing the dose of a sufficient concentration to be applied in the field (Joseph and Morrison 2006). Nanotechnological interventions in agriculture aim to stimulate the natural process with further scientific articulation (Fig. 5). For instance, nanotechnology-based nutrient management mainly relies on two vital factors: an abundance of bioavailable ions in the soil and the plant-soil system’s ionic exchange mechanism (Mousavi and Rezaei 2011). The use of nanoparticles will facilitate the rate of nutrient availability to the plants and ensure proper growth (Mukhopadhyay 2014).

Mitigation of abiotic stresses using biologically synthesized nanoparticles and their valorized products

Field crops

The unique properties of nanoparticles can be utilized in the agricultural sector, especially to promote growth and

Fig. 5 Nanotechnological interventions for abiotic and biotic stress management in agriculture and crop yield optimization



increase tolerance toward abiotic stresses. It has also been observed that plants produce natural mineral-based nanoparticles required for their growth (Wang et al. 2001). The most commonly faced abiotic stresses by crop plants include salinity fluctuation, drought, mineral deficiencies, submergence, non-optimal temperature, and low soil fertility (Boyer 1982; Bulgari et al. 2019). However, among these stresses, drought, salinity, and cold temperature are mainly responsible for reduced crop yield. Hence, these stressors left the plant with no options but to adjust to various unfavorable environmental conditions. After that, they modulate their physiological pathways as defense strategies against stressors. The majority of crop plants are susceptible to salinity fluctuation resulting in reduced productivity (Flowers 2004). The reclamation effects of various nanoparticles against abiotic stresses are presented in Table 5. The use of nanofertilizers can effectively enhance the uptake of nutrients by crop plants and minimize the usage and toxic effect of pesticides and fertilizers in the soil (Saxena et al. 2016). Raven (1983) observed that silicon nanoparticles could reduce Na^+ ion absorption by the crop plants and help the plant grow under high salinity and high Na^+ ion concentration. The application of silicon nanoparticles in field crops enhances the activity of antioxidant enzymes, immobilization of metallic ions, enhances nutrient uptake, facilitates coprecipitation of toxic ions, and ultimately resulted in abiotic stress tolerance (Liang et al. 2007). It has been determined that silicon nanoparticles can ease the cadmium stress in rice as it enhances the proportion of live cells. However,

the extent of stress reduction gradually decreases as the size of the silicon nanoparticles increase. Under cadmium toxicity, when the plant cells are exposed to SiNPs, they remain intact, whereas in the absence of SiNPs, the morphological growth of the plant is hampered (Cui et al. 2017). Under salinity stress, silicon nanoparticles can significantly increase the germination process and seedling growth of lentil plants. In contrast, a considerable reduction in seed germination was observed on lentil crops under salinity stress without the application of Si nanoparticles. Silicon nanoparticles were also reported to positively impact salinity stress in squash (Siddiqui et al. 2014) and faba bean (Qados 2015). Henceforth, it is evident that Si nanoparticles can alleviate the defense mechanism in plants under salinity fluctuation (Sabaghnia and Janmohammad 2015).

It was observed that under water deficit conditions, the application of TiO_2 nanomaterials could positively impact the wheat plant's growth (Jaberzadeh et al. 2013). TiO_2 nanomaterials are photocatalytic, which can stimulate the redox reaction and lead to hydroxide and superoxide radicals. However, a significant impact of TiO_2 nanomaterials was observed in the chloroplasts of the plant *Spinacia oleracea*, regulating the photochemical reaction (Hong et al. 2005).

Moringa oleifera leaf extract-derived silver nanoparticles when applied to the wheat plant's trifoliate stage, can significantly improve morphological growth under heat stress (Iqbal et al. 2019). Under the stress of submergence, silver nanoparticle-treated soybean plants are

Table 5 Application of nanoparticles in crop plants for abiotic stress mitigation

Abiotic stress	Nanoparticles used	Field crops	Effect observed	References
Salt	Nitrous oxide coated with chitosan NPs	Maize	Resulted in a higher leaf S-nitrosothiol content	Oliveira et al. (2016)
Drought, salinity	Zn NPs fertilizers	Wheat	Reduce Cd heavy metal toxicity such as toxicity	Baybordi (2005)
Drought	Silver NPs	Lentil	Enhanced germination root length and increased weight of the lentil seeds	Hojjat and Ganjali (2016)
Salinity	Nano ZnO and Fe ₃ O ₄	<i>Moringa peregrina</i>	Reduced Na ⁺ and Cl ⁻ contents and increased P, N, K ⁺ , Mg ²⁺ , Ca ²⁺ , Zn, Fe concentration	Soliman et al. (2015)
Flooding	Nano Al ₂ O ₃	Soybean	Stimulate energy metabolism and improved growth	Mustafa et al. (2015)
Drought	NanoTiO ₂ , Nano-SiO ₂	Cotton plants	Increased pigmentation, total phenolics, total soluble sugars, concentration of soluble proteins, proline and antioxidant content	Singh and Lee (2016)
Salt	Selenium NPs	Barley	Increase in total phenols, and significant reduction of malondialdehyde (a marker for the ROS-mediated cell membrane damage)	Habibi and Aleyasin (2020)
Cold stress	TiO ₂ NPs	<i>Cicer arietinum</i> L (Chickpea)	Reduced malondialdehyde and electrolyte leakage index (ELI)	Mohammadi et al. (2013)
Drought stress	ZnO NPs	<i>Cicer arietinum</i> L	Enhanced seed germination and promote seedling growth	Cakmak (2008)
Drought	Nano-TiO ₂	<i>Borago officinalis</i> L	Increased photosynthetic efficiency	Akbari et al. (2014)
Salinity, water deficit	Silica NPs	Cucumber	High concentration of silicon found in cucumber leaf regulates water loss through transpiration	Alsaeedi et al. (2019)
Salinity	Fe NPs along with K silicate	Grape	Significantly increase total protein content and free prolin level and also influence enzymatic antioxidant activity thus lowers hydrogen peroxide concentration	Mozafari. and Ghaderi (2018)
Drought	Fullerenol NPs	Sugar beets	Fullerenol NPs act as an intracellular binder of water while creating additional water reserve, thus enabling adaptation to drought stress	Borišev et al. (2016)

believed to encounter reduced oxygen deprivation stress compared to untreated soybean. The enhanced growth in silver nanoparticle-treated soybean plants during flooding is mainly due to the downregulation of the *pyruvate decarboxylase 2* and *alcohol dehydrogenase 1* genes (Mustafa et al. 2015). In addition to that, zinc oxide nanoparticles

can significantly increase the germination of soybean seeds under water stress (Sedghi et al. 2013). Upregulation of antioxidant enzymes like catalase and superoxide dismutase is attributed to nanoparticles' application under stressed conditions (Laware and Raskar 2014).

Horticulture crops

Focusing on horticultural crops, resistance against abiotic stresses is crucial as their market value is comparatively higher than the field crops. They are the source of various nutrients like carbohydrates, minerals, and fiber (Shannon and Grieve 1998). Abiotic stresses hamper the yield and worsen the quality triggering physiological, morphological, and biochemical changes, which lead to a change in nutraceutical value or visual appearance (Rao et al. 2016). In plants, including horticultural crops, various minerals are considered essential microelements for proper physiological responses, but they are sometimes insufficiently found in the soil. For instance, iron is available in the Fe^{3+} form in the soil with high pH, and the soil becomes deficient in the Fe^{2+} form of iron, causing iron deficiencies (Rui et al. 2016). To address this mineral deficiency in the soil, nanoparticles can be employed to address this mineral deficiency. Due to faster translocation and low wastage of nanoparticle-based fertilizers into the plants, their usage is widely accepted (Zahedi et al. 2019). Nanocomposites, including macro- and micro-nutrients, are formulated using nanotechnological techniques to have desirable properties that help prevent nutrient leaching from the water and soil (Barrios et al. 2016). Nanoparticles can quickly enter the cells and bind with the carrier proteins and stimulate nutrient delivery through endocytosis, ion channels, or aquaporins (Rico et al. 2011).

Among various metallic oxides, iron oxide nanoparticles are also available in nature in the form of nanocrystals of maghemite (Fe_2O_3) and magnetite (Fe_3O_4). Additionally, magnetite (Fe_3O_4) nanoparticle has the potential to absorb various toxic heavy metals like cadmium. This nanoparticle's cadmium removal activity was demonstrated in tomato plants during heavy metal contamination (Rahmatizadeh et al. 2019).

Apart from iron nanoparticles, Si nanoparticles showed promising results on morphological and physiological traits of basil plants exposed to salinity stress (Kalteh et al. 2018). When the salt-affected basil plant is treated with silicon nanoparticles, it causes a significant rise in proline and chlorophyll concentration and induces mitigation against salinity stress. Application of SiO_2 nanoparticles in tomato plants under salt toxicity resulted in enhanced germination of seeds and activated antioxidant response for stress mitigation (Haghighi and Pourkhaloe 2013).

In fruit crops like strawberries, nanomaterials can be directly sprayed on the plants. The application of nanoparticles in grapes (Sabir et al. 2014) and strawberry plants (Zahedi et al. 2019) was reported to decrease the lethal effects of alkalinity and salinity fluctuation, respectively. Fruit crops treated with nanoparticles are comparatively vigorous and can withstand abiotic stress while maintaining fruit quality (Zahedi et al. 2020). Selenium nanoparticles

can improve salinity tolerance in strawberry plants and subsequently increase the yield (Zahedi et al. 2019). A follicular spray of selenium nanoparticles in pomegranate under drought stress prevents the fruits from cracking (Zahedi et al. 2020). Water-soluble carbon nanoparticles (CNPs) can promote seed germination in lettuce under salt stress. Carbon nanoparticles can restrict primary root elongation but promote chlorophyll accumulation and lateral root growth at high salinity conditions (Baz et al. 2020). Although most plant species have a defense system to cope with adverse environmental conditions, the defense mechanism sometimes initiates very late. Hence, the plants should be assisted by applying various stimulators like nanostructured materials (Brown and Saa 2015).

Mitigation of biotic stresses using biologically synthesized nanoparticles and their valorized products

Field crops

Conservation and improvement of crops can be achieved by plant breeding, applying pesticides, and ensuring regular sanitation. However, the quality and total crop yield are restricted due to pathogens/pest infestation. Diseases in plants are mainly caused by bacteria, viruses, nematodes, and fungi resulting in economic loss, reduced production, and crop quality (Servin et al. 2015). Hence, the optimization of crop yield requires extreme usage of traditional crop management methods. The traditional methods are quite expensive, and the crop tends to develop gradual resistance with time. In this context, antimicrobial properties associated with nanoparticles are employed to suppress pathogens and improve crop yield and quality. The antimicrobial properties of nanoparticles are attributed to specific mechanisms (Lemire et al. 2013; Zeng et al. 2007). Nanoparticles can alter the functional membrane protein of the pathogen and regulate cell permeability by liberating toxic ions while assisting nutrient uptake by the plants. They also cause genotoxicity and oxidative damage to pathogens as they interact with pathogenic DNA. As the nanoparticles enter the microbial cells, they tend to produce reactive oxygen species, oxidizing the macromolecules of bacterial cells (Musee et al. 2011). Nanomaterials such as titanium oxide NP, silver NP, single-walled carbon nanotubes, and fullerene C60 NP exhibit antibacterial properties in bacterial monoculture (Morones et al. 2005; Lyon et al. 2006). Therefore, the microbicidal property of nanoparticles can be utilized to mitigate biotic stresses in crop plants.

Among various pathogenic microorganisms, fungi cause numerous infectious diseases in crop plants and are highly detrimental. Cu, Ti, Si, and Zn nanoparticles possess promising antifungal properties and thus prevent fungal attacks. When

two different rice varieties, such as Mongolian (susceptible to fungal infestation) and fungus-resistant Nongda 18, were treated with Si nanoparticles, they showed inhibitory action against a fungal pathogen, *M. grisea* (Dubey et al. 2018). It has been suggested that ZnO nanoparticles are comparatively more advantageous than Ag nanoparticles in treating fungal pathogens, *Fusarium graminearum*, and suppressing crop diseases (Dimpka et al. 2013). Chitosan-based nanostructured materials are widely used to control fungal diseases across the globe. The diverse characteristics of the chitosan nanostructures include high permeability, biodegradability, cost-effectiveness, and non-toxic nature. Under in vitro conditions, chitosan nanoparticles showed antifungal property against various phytopathogenic fungi. The chitosan-based nanoparticle was examined for suppressing the fungal pathogen, *Pyricularia grisea*, causing leaf blast disease in rice plants, and showed a significant result in suppressing the devastating fungus (Manikandan and Sathiyabama 2016). Similarly, bio-fabricated silver nanoparticles using *Serratia* sp. (bacterium) were scrutinized for their effectiveness against spot blotch disease in wheat. The biosynthesized AgNPs showed antifungal properties against the fungal pathogen *Bipolaris sorokiniana* and induce lignin deposition in vascular bundles of wheat (Mishra et al. 2014). Biologically synthesized zinc oxide nanoparticles, using extracts of olive leave, red tomatoes, and chamomile flowers, showed promising results in controlling bacterial phytopathogen causing leaf blight disease of rice plants (Ogunyemi et al. 2019). Park et al. (2006) reported the antimicrobial activity of silica-silver nanosized particles against various phytopathogens such as *Colletotrichum* sp., *Pythium* sp., *Xanthomonas compestris*, and *Pseudomonas syringae*. Additionally, this formulation can efficiently control the powdery mildew disease of pumpkin at greenhouse and field conditions. Likewise, silver nanoparticle-treated chickpeas are better equipped to withstand collar rot disease in greenhouse conditions (Mishra et al. 2017). It has also been reported that Al₂O₃, ZnO, and silver nanoparticles are effective against phytopathogenic nematodes viz. *Caenorhabditis elegans*, but the nematode larvae's mortality rate depends on the nanoparticle concentration and exposure time (Wang et al. 2009). Apart from these metallic nanoparticles, titanium oxide-graphene composite film was also reported to exhibit a significant solar light irradiation-induced cytotoxicity on nematode, *Caenorhabditis elegans* (Akhavan et al. 2012a), which can be attributed to the fact that the photoexcited TiO₂-graphene composite can effectively photoinactivate the nematodes thriving in a culture medium, as they tend to form high-level reactive oxygen species causing oxidative damage to the nematode cells. Further, TiO₂-graphene composite exhibits photocatalytic properties and is employed for the formation of Ti–O–C and Ti–C bonds at 450 °C which facilitates the charge transfer between photoexcited graphene and titanium oxide.

Horticulture crops

The application of nanoparticles in agriculture can control biological agents like phytopathogens and pests while uplifting the agricultural economy. The silver nanoparticle's inhibitory action to prevent powdery mildew in cucumber and pumpkin was investigated under field conditions. It was suggested that the inhibition is attributed to the accumulation of silver in the fungal hyphae, which disrupts the fungal cell (Servin et al. 2015). Comprehensive studies were conducted to investigate the inhibitory effect of silver NP in controlling gray mold disease in strawberries (Moussa et al. 2013) and *Pseudomonas syringae* infestation in tomatoes (Chu et al. 2012). Antifungal efficacy of copper-chitosan NP against *Fusarium oxysporum* and *Alternaria solani* under in vitro conditions was reported. The formulation showed a significant result in controlling fusarium wilt and early blight disease in tomato plants (Saharan et al. 2015).

Copper oxide nanoparticles are also used as a fungicidal compound to protect banana, tea, cocoa, coffee, citrus fruits, and other important horticultural crops from various fungal diseases like powdery mildew and rust blight disease (Kiaune and Singhasemanon 2011). The antifungal property of Cu-based nanoparticles on *Phytophthora infestans* in tomato plants suggested promising results compared to other agrochemicals (Giannousi et al. 2013). These nanocoppers can prevent bacterial blight in pomegranate as they inhibit the growth of *Xanthomonas axonopodis* pv. *Punicae* (Mondal and Mani 2012).

In this aspect, nanogelled pheromones are also employed to catch *Bactrocera dorsalis*, a harmful pest, thus reducing its detrimental effect without using any toxic chemicals. This nanogel formulation restricts the process of evaporation and induces the release of pheromones, which enables the transportation of various fruits like guava without freezing (Vargas et al. 2009). Nanogelled pheromones are also used to entrap the fruit flies; when placed on the water surface, they attract the fruit flies and entrap them in the water (Bhagat et al. 2013). Therefore, it is evident that nanostructured materials under stressed conditions can significantly stimulate the plants' defense system. The role of various nanoparticles for biotic stress mitigation is presented in Table 6.

Mitigation of multiple stresses using valorized products

Field crops

Stress management in crop plants using manganese (Mn) nanoparticles has been scrutinized to reduce the adverse effects caused by harsh temperature, salinity, and drought (Ye et al. 2019). The result showed that Mn NPs help the crops overcome different abiotic stresses with high

Table 6 Application of nanoparticles in agricultural crops for biotic stress mitigation

Type of biotic stress	Crop type	Nanoparticles used	Effect	References
Rice blast disease (<i>Magnaporthe grisea</i>)	Rice	Silver NP	Effectively reduce the severity of the disease	Jo et al. (2009)
Leaf spot disease (<i>X. campestris</i> pv. <i>Phaseoli</i>)	Mung	Nano-copper	Effective reduction in bacterial disease	Rani et al. (2015)
<i>Fusarium oxysporum</i>	Maize	Silicon NP	Showed significantly higher resistance	Suriyaprabha et al. (2013)
<i>Aspergillus niger</i>				
<i>Pyricularia grisea</i>	Finger millet	Copper-chitosan NP	Considerable increase in defensive enzyme activity and suppression of blast disease	Sathiyabama and Manikandan (2018)
<i>Botrytis cinerea</i> (preharvest preservation of strawberry)	Strawberry	ZnO NP	Significant delay in spoilage of strawberry when the ZnO NP was applied in the field	Luksiene et al. (2020)
<i>Spodoptera littoralis</i>	Tomato	Nano-silica	Nano-silica affects the feeding preference of <i>Spodoptera littoralis</i> , thus increasing the resistance of tomato plants	El-Bendary and El-Helaly (2013)
Root-knot nematode (<i>Meloidogyne incognita</i>)	Tomato	Selenium NP	Effecting the physiological and morphological parameters of the parasites	Udalova et al. (2018)

efficiency and reduce toxicity compared to other ionic counterparts. Also, the effect of TiO₂ nanoparticles (NPs) on the physiological responses of chickpea (*Cicer arietinum* L.) was studied under cold sensitivity (Mohammadi et al. 2014). As the plants were treated with TiO₂ NPs under temperature stress, they showed a significant decrease in electrolyte leakage index, hydrogen peroxide (H₂O₂) level, and malonaldehyde (MDA) concentration compared to control plants. These physiological changes allow the plant to withstand cold stress.

Nanomaterials such as silica NP has been successfully demonstrated to transfer targeted genes into various cells (Torney 2009). Therefore, they can be deployed to formulate many insect repellants, pesticides, and insecticides (Barik et al. 2008). Hollow silica NP loaded with pesticide, validamycin, can ensure the chemical-controlled release (Liu et al. 2006). Besides, nanoalumina is also used as an insect repellent against *Rhizopertha dominica* (F.) and *S. oryzae* L. in stored food items (Stadler et al. 2010).

Underwater deficit condition, nano-TiO₂ was investigated to activate the faba bean defense mechanism (*Vicia faba* L.) (Khan et al. 2020). Application of nTiO₂ (15 mg/l) to the stressed plants showed a significant increase in nitrate reductase (NR) activity and induced the synthesis of nitric oxide (NO), therefore elevating the process of the enzymatic and non-enzymatic defense mechanism of the plants. It can also suppress electrolyte loss, lipid peroxidation, and the generation of H₂O₂. TiO₂ nanoparticles, along with NO, can enhance osmolyte accumulation and assist plants in maintaining osmotic balance.

Horticulture crops

During various abiotic pressures such as drought, salinity fluctuation, heavy metal contamination, and thermal stress, one of the major responses by the plants is the synthesis of reactive oxygen species-singlet oxygen, superoxide ions, hydroxyl radicals, and hydrogen peroxide, leading to severe damage to the cells and organelles. To alleviate the damage, plants tend to develop a complex antioxidant mechanism for maintaining homeostasis. Application of exogenous Si has been observed to induce the stress tolerance ability of the plant by regulating ROS generation and decreasing the uptake of various toxic ions such as Na, in stressful conditions. Another report suggested that the application of fullerene and nanosilica on cucumber leaves reduces the uptake and toxicity of metalloids during exposure (Guo et al. 2019). The plants showed a significant difference in disease resistance at different levels of nanomaterial application.

The effect of silica NPs in enhancing the growth and yield of cucumber plants under salinity stress and water deficit condition was assessed (Alsaedi et al. 2019). It has been concluded that Si NPs can improve the morphological growth and overall productivity of cucumbers regardless of the quantity of water supplied. During salinity stress and water deficit conditions, a high concentration of silicon in the leaves helps regulate water loss through transpiration. Moreover, a high level of K⁺ ion present in cucumber roots helps to withstand the abiotic stresses and regulate the osmotic concentration. SiNPs also help control the plants' stomatal opening and induce their adaptability against salt toxicity and drought.

Cytotoxicity and action mechanisms of nanostructured materials obtained from agricultural wastes

Rapid growth in the nanotechnology sector through the abundant use of metallic nanoparticles in a wide range of consumer/antibacterial products and industrial applications lead to the inevitable discharge of these NPs into aquatic environments, and waste streams created concerns about potential impacts on aquatic ecosystems' safety, animal and plant health (Bone et al. 2015; Jiang et al. 2017). Studying the impact of emerging pollutants such as nanoparticles is necessary to identify their adverse effects. Several manufactured nanomaterials (NM) are being used in consumer products, and exposure modeling predicts releases of ng to low $\mu\text{g/l}$ levels of NMs into surface waters (Handy et al. 2011). The exposure of manufactured NMs to aquatic ecosystems and consequently to fish is inevitable. There is a risk of exposure to aquatic organisms to silver nanoparticles from municipal and industrial wastewater discharges. The manufactured NMs are less toxic compared to some traditional dissolved metals. Bruneau et al. (2016) investigated the fate, the bioavailability of AgNPs, their harmful effects on fish in the presence of municipal effluents as AgNPs in wastewater, and their bioavailability to fish. The acute toxicity data suggest that the lethal and sublethal concentrations for many NMs are in the ranges of mg/l and 100 μg to 1 mg/l, respectively (Handy et al. 2011).

Kumar et al. (2018c, d) have successfully demonstrated that the AChE activities were inhibited on exposure to contamination to fishes by the stressor group (Pb and high-temperature exposure group) and supplemented group of AgNP at 1 mg/kg. Similarly, the two mg SeNPs/kg diet induces immunosuppression with a negative effect on growth performance, antioxidative status, and innate immune responses (Kumar et al. 2017a, 2018a, b). Ashouri et al. (2015) have reported that a 1 mg nano-Se per kg diet improved common carp growth but 2 mg/kg showed toxicity.

A moderate level of selenium enrichment (~ 4 mg/kg dry matter) influences the rearing efficiency of fish larvae, but higher dosages could cause adverse effects (Juhász et al. 2017). Se NP exhibited strong toxicity for Medaka approximately fivefold difference in terms of LC50 compared to selenite due to hyper-accumulation of Se in the liver and oxidative stress (Li et al. 2008). Significant improvements were observed in survival, growth, digestive enzyme activities, concentrations of biochemical constituents, and total and differential hemocyte count of prawns fed with 20 mg Cu-NPs (200 nm)/kg supplemented feed but 40–80 mg Cu-NPs/kg supplemented feed showed negative performance of *Macrobrachium rosenbergii* (Muralisankar et al. 2016).

The widespread usage of AgNPs can pollute inland and marine environments. These NPs activate the production of

free radical reactive species in aquatic organisms that hinder DNA function causing mitochondrial dysfunction and increasing lipid peroxidation terminating development and reproduction (Ramzan et al. 2022). AgNPs are oxidized to Ag⁺ ions by the dissolution process and react with the negatively charged oxygen and nitrogen atoms in DNA, mitochondrion, and the thiol group presented in protein structures and enzymes, which in turn hinder normal cell reproduction leading to cell death (Ghobashy et al. 2021). Martin et al. (2017) have found that exposure to the high concentration of AgNPs for a long duration considerably increased lipid peroxidation in the gill tissue of yellow perch (*Perca flavescens*). Forouhar Vajargah et al. (2019) have examined the effects of AgNPs on hematological, biochemical, and gonad histopathological indices of male goldfish, which showed that a single dose of a slight amount of silver nanoparticles could enhance the shrimp immune system's response without toxic effects in healthy shrimps. Abbas et al. (2019) have demonstrated that biochar can be used effectively to prevent the bioaccumulation and subsequent trophic level transfer of Ag nanopollutant in the environment.

Multiple mechanisms have been proposed to underlie the bactericidal activity of AgNPs. Cytotoxicity of AgNPs is implicated in their bactericidal activity, which is influenced by their size and shape, giving rise to various action mechanisms against pathogens (De Silva et al. 2021). The known mechanisms involved in the cytotoxicity of nanomaterials are as follows:

1. *Attachment to cellular membranes through direct physical interaction of extremely sharp edges of nanomaterials with cellular membranes:* The cell wall destruction that occurs from the physical interaction between NPs and the cell wall is more detrimental for Gram-negative bacteria as they lack the thick peptidoglycan layer found in Gram-positive bacteria that could possibly act as a protective layer (Slavin et al. 2017). Both Gram-positive and Gram-negative bacteria have a negatively charged cell wall, which influences the interactions between the cell walls and NPs or ions. Sharp-edged graphene nanowall immobilized on stainless steel caused extreme physical damage to the bacterial cell wall of Gram-positive bacteria, *Staphylococcus aureus* lacking the outer cell lipopolysaccharide membrane (Akhavan and Ghaderi 2010), whereas the Gram-negative *Escherichia coli* bacteria with an outer membrane were more resistant to the cell membrane damage caused by the nanowalls, as *E. coli* is more negatively charged and rigid than *S. aureus* (Sonohara et al. 1995).
2. *Activation of reactive oxygen species (ROS):* Nanostructured materials can potentially lead to the production of free radicals especially reactive oxygen species

- (ROS) within the bacterial cell causing cell damage. It has been reported that reduced graphene oxide contributes to the formation of ROS under the influence of the visible light spectrum which instantly kills *Enterobacter* sp. (Dutta et al. 2015). Similarly, Liu et al. (2018) reported the enhanced antibacterial functionality of zinc oxide/graphene quantum dot nanocomposites under UV photoirradiation as compared to that in ambient light conditions, which has been accredited by the increased production of highly unstable reactive oxygen species. On the contrary, capped zinc oxide nanoparticle generates reactive oxygen species such as H_2O_2 , O^- , and OH^- even in dark condition, showing antibacterial activity, which can be ascribed due to the presence of defective nanosurfaces of the capped nanomaterials (Lakshmi Prasanna and Vijayaraghavan, 2015).
3. Trapping of bacteria within the aggregated nanomaterials: Akhavan et al. (2011) reported that the bioactivity of *Escherichia coli* can be restricted by entrapping the bacteria within aggregated graphene nanosheets. The bacterial cell trapped inside the aggregated sheets neither consume glucose for their survival nor can proliferate in the culture medium as they get detached from their ambient environment, which can further be inactivated photothermally using near-infrared irradiation. Graphene nanosheets have successfully been demonstrated for encapsulation of pathogenic bacteria for complete inactivation.
 4. Intracellular damage through oxidative stress: Nanoparticle-induced oxidative stress mechanism has been reported by Liu et al. (2011) using four types of cytotoxic graphene-based nanocomposites for their antibacterial activity against a bacterial model—*Escherichia coli*. Dutta et al. (2015) and Liu et al. (2018) documented that nanoparticles can potentially produce ROS, irrespective of light and dark conditions, leading to oxidative stress in the bacterial cell.
 5. Interrupted glycolysis process: Lee et al. (2016) studied the effect of AgNPs on the glucose metabolism process in hepatic cell lines and suggested that silver nanoparticles can lead to increased production of ROS and thus affect the glycolysis process; however, the process of glucose metabolism can be restored in the presence of ROS scavengers. Similarly, Wang et al. (2019) observed that nanoparticles can degenerate the enzymes required for glycolysis and TCA cycle, causing suppressed cellular oxidative stress response and systemic cell death in the bacterium, *E. coli*.
 6. DNA damaging: Akhavan et al. (2012a, b) investigated the genotoxicity effect of reduced graphene oxide nanoplatelets against human mesenchymal stem cells and successfully demonstrated that this not only damages the cell membrane via oxidative stress but also causes cytotoxic and genotoxic effects on stem cells through chromosomal aberrations and DNA fragmentation.
 7. Ion release: Wang et al. (2014) reported that zinc oxide/graphene oxide nanocomposites release ions, as and when come in contact with *E. coli*. Graphene oxide regulates the dissolution of zinc oxide and enables the bactericidal activity of the nanoparticles. The close association of ZnO with *E. coli* enhances the permeability of Zn ion in the bacterial cells and thus induces bacterial death. The antimicrobial activity of silver NPs can be attributed to the release of Ag^+ ions and their subsequent interaction with sulfhydryl groups of intracellular and membrane proteins as well as with DNA (Königs et al. 2015).
 8. Formation and explosion of nanobubbles: Oxygen-containing nanobubbles have a wide range of pharmacological and physiological effects including tissue repair mechanisms, anti-inflammatory properties, antibacterial activity, and tissue oxygenation. Jannesari et al. (2020) have successfully demonstrated the superior antibacterial properties of reduced graphene oxide/copper peroxide-based oxygen nanoshuttle/nanobubbles on Gram-positive bacteria (*S. aureus*) compared to Gram-negative bacteria (*E. coli*) and concluded that the O_2 -containing nanoshuttles can effectively be used as controllable and intelligent anti-infection nanorobots in future graphene-based nanobiomedical applications. They have reported that reduced graphene oxide contents could provide synergistic effects by harvesting some respiratory electrons from the bacteria and transferring them into the O_2 nanobubbles, which leads to the formation of nanoscale-ROS. COVID-19 patients with acute hypoxemic respiratory failure were treated with O_2 -containing nanobubbles because of their multimodal functions including antimicrobial, anti-inflammatory, drug-carrying capacity, and the promotion of wound healing (Afshari et al. 2021).
 9. Inducing the viable but non-culturable state of pathogens (VBNC): VBNC is a unique state, which is a survival strategy for a number of bacteria under stressed and harsh environmental conditions. Xiao et al. (2021) reported that the majority of *E. coli* cells fell into a VBNC state, rather than became dead when exposed to AgNPs in natural water. Königs et al. (2015) have observed that silver-exposed bacteria can enter the VBNC state, which is important for a realistic assessment of the antimicrobial properties of AgNPs. In the VBNC state, bacterial cells are metabolically active, but unable to carry out cell division due to inhibition of key functions including a reduced rate of nutrient transport, uptake of important substrates, and synthesis of macromolecules causing structural and morphological changes to the bacterial cell membrane.

There is a need to pay attention to the physicochemical characteristics of NPs (size, charge, zeta potential, surface morphology, and crystal structure), environmental conditions, and the metabolic pathways of microorganisms for understating antimicrobial mechanisms. The significant elements that control NP action on microbes include oxidative stress induction, the release of metal ions, and non-oxidative mechanisms (Wang et al. 2017). Although metallic NPs show their antimicrobial effects dominantly through membrane protein damage and the generation of superoxide radicals and ions that interfere with the cell granules leading to the formation of condensed particles (Shaikh et al. 2019), their antimicrobial potential and action mechanisms are yet altered, which is further evidenced by the fact that in many investigations, the antimicrobial activities have been attributable to oxidative stress/ROS, but in many studies for other NPs, the antibacterial mechanism are not linked with the regulation of bacterial metabolism.

Conclusion

Biologically synthesized metallic and non-metallic nanoparticles have been used as therapeutic agents and diagnostic in the human medical field. However, their application in crops, livestock, aquaculture, and fisheries is still relatively new. The present review focused on the current status and recent advances in innovative methods for synthesizing metallic and metallic nanoparticles using plants, animals, and fisheries wastes and their valorization to mitigate abiotic and biotic stresses, for nutrient delivery, antimicrobial agents, and tools in agriculture. With continued exploration and refinement in nanobiotechnological interventions, nanostructured materials could play a significant role in the crop, animal, and fish production. A variety of nanostructured materials can very well be prepared using crop plantation biomass residues, animal discards, fisheries waste, and consequently addressing the environmental issue. This may help control environmental pollution through the crop, animal, and fish solid waste management and control the different diseases. Nanotechnology research in the fields of crop plants, and animal and fish production are still in its primitive stage, but encouraging results from nanobioremedial, antimicrobial, nutritional, and reproductive studies drive the further investigation. The novel, innovative, and responsible nanotechnology development should continue, with potential benefits for aquaculture, culture-based fisheries, and fish health diagnostics. This review will strengthen advanced research on nanotechnological interventions for achieving nanobioremedial, antimicrobial, nutritional, climate-smart, and stress-resilient agriculture. The dominating antimicrobial mechanisms of metallic and non-metallic NPs need to

be understood properly and are worthy to be researched further to explore the method of alleviating antimicrobial resistance.

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Declarations

Ethical approval We hereby declare that the manuscript is original work by the authors and has not been submitted for publication elsewhere. We further certify that proper citations to the previously reported work have been given and no data/table/figures have been quoted verbatim from other publications without giving due acknowledgments and without the permission of the author(s).

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