Materials Today Bio 22 (2023) 100759

Contents lists available at ScienceDirect

Materials Today Bio

journal homepage: www.journals.elsevier.com/materials-today-bio

Nanobiotechnology to advance stress resilience in plants: Current opportunities and challenges

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ARTICLE INFO

Keywords:
Agriculture
Nanotechnology
Stress resilience
Nanosensors
Health risks

ABSTRACT

A sustainable and resilient crop production system is essential to meet the global food demands. Traditional chemical-based farming practices have become ineffective due to increased population pressures and extreme climate variations. Recently, nanobiotechnology is considered to be a promising approach for sustainable crop production by improving the targeted nutrient delivery, pest management efficacy, genome editing efficiency, and smart plant sensor implications. This review provides deeper mechanistic insights into the potential applications of engineered nanomaterials for improved crop stress resilience and productivity. We also have discussed the technology readiness level of nano-based strategies to provide a clear picture of our current perspectives of the field. Current challenges and implications in the way of upscaling nanobiotechnology in the crop production are discussed along with the regulatory requirements to mitigate associated risks and facilitate public acceptability in order to develop research objectives that facilitate a sustainable nano-enabled Agri-tech revolution. Conclusively, this review not only highlights the importance of nano-enabled approaches in improving crop health, but also demonstrated their roles to counter global food security concerns.

1. Introduction

The food production and distribution chain is under tremendous pressure due to various factors, including abrupt climate change, population growth, water scarcity, and soil contamination [1]. The diminishing arable land because of urbanization and industrialization further compounds the issue, making food security the biggest concern of the century [2]. To meet global food demand, more productive and stress resilient system is crucial. Although the crop production system has improved significantly since the green revolution, but it cannot be sustained without technological advancements [3]. Furthermore, the inefficient utilization of agrochemicals has jeopardized sustainable crop production. The use of synthetic fertilizers is detrimental to plant sustainability due to low nutrient efficacy, increased environmental risks, higher production costs, and reduced farmer profitability [4]. Traditional breeding methods have indeed played a significant role in enhancing agricultural traits and crop productivity over time. However, these methods can be time-consuming due to approaches such as pure

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https://doi.org/10.1016/j.mtbio.2023.100759
Received 31 May 2023; Received in revised form 3 August 2023; Accepted 4 August 2023
Available online 6 August 2023

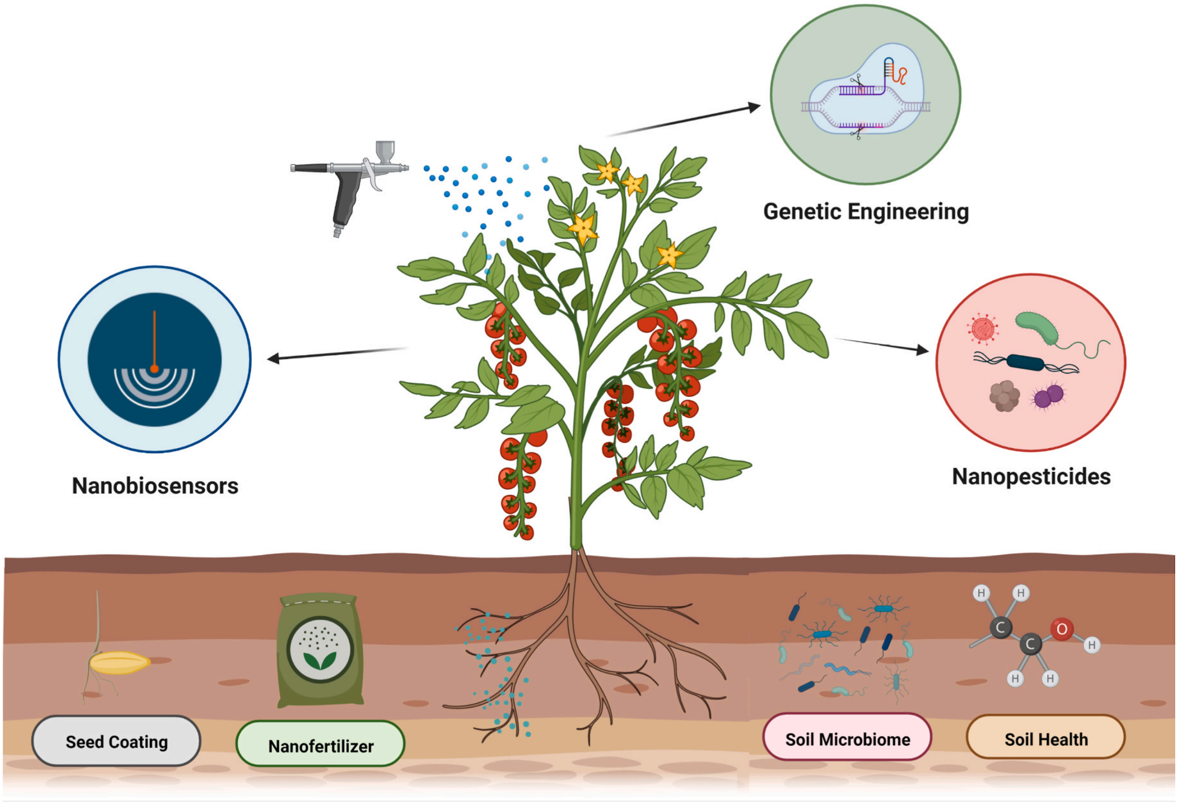

Fig. 1. Potential applications of ENMs in sustainable agriculture for improving stress resilience of crop plants. ENMs can be used as nanobiosensors by coating materials for seeds, as nanofertilizers to improve soil microbiome and soil health, as nanopesticides to control pathogens and as nanocarriers to assist genetic engineering. This figure is created by using BioRender (https://biorender.com/).

line selection, backcrossing, and single seed descent, and they may face limitations in introducing new traits between species, which can hinder the rapid development of improved varieties [5]. Additionally, there is growing recognition that current agricultural practices need to evolve towards more sustainable and efficient methods to address environmental concerns and ensure long-term ecological balance [6]. Therefore, a technological revolution in making stress resilient crop management system is necessary to sustainably meet global food demands in the future.

Nanotechnology has been integrated with various scientific fields to create innovative products and technologies to improve the traits of crop plants [7]. Agri-nanotechnology is aimed at improving crop productivity with efficiently managed inputs e.g., fertilizers, pesticides, and agrochemicals mediated by real-time monitoring systems. A variety of nanotechnology applications will make a positive impact on crop productivity and quality at all stages of agriculture from seed germination to post-harvesting [8]. Engineered nanomaterials (ENMs) are the key players in the Agri-tech revolution. The nanoscale sizing of these materials (<100 nm) enables them to overcome the biological barriers to ensure efficient delivery of pesticides and nutrients through foliar or root applications [9]. Moreover, heavy metals and environmental pollutants can be detected in soil media by using NM-based optical and electrochemical sensors. ENMs, which are capable of being used as sensors in plants, are ideally suited to driving this change, enabling large-scale monitoring of crop health at temporal and high spatial resolution [10].

ENMs structural and physio-chemical characteristics can be modified through engineering to alter their route of delivery and mode of action for smart delivery and release of the active ingredients to the desired location [11]. CRISPR has revolutionized the potential of genome editing technology. The biggest hurdle in its application in genome manipulation is its limited efficiency of intracellular delivery that severely compromises the success ratio. Several ENMs act as non-viral nanocarriers and have shown great ability for the delivery of genes, along with polymers, liposomes, and inorganic nanoparticles [5]. Nanotechnology also helps in mitigating the preharvest food loss by providing targeted delivery of nutrients and additives leading to more efficient utilization of resources, and the improved management of stress and disease. The aforementioned features make ENMs a potential candidate for sustainable agriculture [12].

This review focuses on providing deeper insights into the potential applications of nano-enabled techniques for improving stress resilience, including smart delivery of micronutrients, smart nano-sensors, nano-based approach for plant genome editing, and limitations associated with the field-scale applications of ENMs. This review is important for understanding the functions of ENMs as a system for improving crop productivity and environmental sustainability.

2. Applications of ENMs in improving stress resilience of crop plants

ENMs offer a versatile range of applications, serving as nanobiosensors by coating materials for seeds, nanofertilizers to improve soil microbiome and soil health, nanopesticides for effective pathogen control, and nanocarriers to aid genetic engineering in crops. These emerging nanotechnology-based solutions have the potential to revolutionize agricultural practices and contribute to the development of resilient and sustainable crop production systems (Fig. 1). Furthermore, ENMs can improve nutrient utilization by targeted delivery, creating affordable resource recovery strategies, developing plants into smart sensors to predict the upcoming stress, creating more resilient cultivars through genetic modifications, improving the management of crops to avoid crop losses, enhancing microbiome to replenish soil quality and elevate plant growth [13]. These steps can result in an improved yield by

Table 1
Systematic evaluation of nano-based strategies for their applications, challenges, and prospects in crop stress management.

Nano-based strategy	Type of NPs used	Plant studied	Improved crop characteristics	Challenges & implications	Recommendations for future	Citations
Nanofertilizers						
Use of nanoparticles for improving nutrient uptake and photosynthesis efficiency	Carbon Nanoparticles (CNPs)	*Zea mays*	Increased crop growth, soil quality, photosynthetic efficiency and nutrient uptake	Lack of understanding in their performance under different soil conditions, their surface characteristics and internalization within plants and soils.	Development of cost-effective and scalable nano-based strategies	[14]
Use of nanoclay-based soil amendments for improving soil properties	Zincated Nanoclay Polymer Composites (ZNCPCs)	–	Increased soil moisture retention and slow release of nutrients	Lack of understanding about the long-term effects of nanoclay on soil health	Further research on the long-term effects of nanoclay-based soil amendments on soil health	[15]
Use of nanomaterials for improving plant-microbe interactions	Pristine (ZnO MNPs) and sulfidized zinc oxide nanoparticles (s-ZnO MNPs)	*Glycine max*	Increased nutrient availability and disease resistance	Limited understanding of the mechanisms underlying plant-microbe interactions	Further research on the mechanisms underlying plant-microbe interactions and the optimization of nanomaterials for enhancing these interactions	[16]
Nanopesticides						
Use of nanopesticides for controlling plant pathogens	Metal NPs (CuO, ZnO, and FeO)	Tomato (for tomato bacterial wilt)	Reduced damage from plant pathogens	Limited understanding of the mechanisms underlying the interaction between nanopesticides and plant pathogens	Further research on the mechanisms underlying the interaction between nanopesticides and plant pathogens, as well as their potential impacts on non-target organisms	[17]
Nano-sensors						
Use of nanoscale sensors for monitoring crop health	FRET nanosensors	*Arabidopsis*	Monitoring of nutrient flux into intact organs	Limited research on the integration of nanosensors with precision agriculture technologies	Development of integrated nanosensor technologies for precision agriculture	[18]
Use of nano-biosensors for detecting plant stress biomarkers	Multiwalled carbon nanotubes-based zinc nanocomposite (ZnO/MWCNT)	Generally applicable	Early detection of stress (viral infection) and timely management	Limited research on the detection of stress biomarkers in across crop varieties	Development of nanobiosensors for detecting stress biomarkers among a range of different crops	[19]
Nano-carriers						
Use of nano-carriers for targeted delivery of stress-responsive genes	Delaminated layered double hydroxide lactate nanosheets (LDH-lactate-NS)	*Populus simonii*	Enhanced stress tolerance and reduced crop losses	Limited research on the stability and efficacy of nanocarriers in field conditions	Further research on the stability and efficacy of nanocarriers in field conditions and optimization of gene delivery systems	[20]
Use of nano-carriers for delivering beneficial microorganisms to crops	Polyethylene oxide (PEO) nanofibers	*Phaseolus vulgaris*	Enhanced plant growth and served as a potential seed coating material	Limited research on the stability and efficacy of nanocarriers for delivering beneficial microorganisms in field conditions	Further research on the stability and efficacy of nanocarriers for delivering beneficial microorganisms in field conditions	[21]
Others						
Use of nano-coatings for protecting crops from environmental stress	Titanium dioxide (TiO_2) nanoparticles	*Plumeria rubra*	Reduced damage from environmental stressors such as UV radiation and extreme temperatures	Limited research on the effectiveness and safety of nanocoatings	Further research on the effectiveness and safety of nanocoatings, including their potential environmental impacts	[22]
Use of nano-clays for reducing heavy metal toxicity in crops	Nanocomposite powder – with titanium (IV) dioxide (TiO2) and montmorillonite clay (MMT)	Palm oil mill effluent	Reduced uptake and accumulation of heavy metals in crops	Limited understanding of the mechanisms underlying the interaction between nanoclays and heavy metals	Further research on the mechanisms underlying the interaction between nanoclays and heavy metals, as well as their potential impacts on soil and plant health	[23]
Use of nanobubble irrigation for improving water use efficiency	Nanobubble water	Watermelon and muskmelon	Reduced water use and increased crop yield	Limited research on the efficacy and scalability of nanobubble irrigation	Further research on the efficacy and scalability of nanobubble irrigation, as well as its potential environmental impacts	[24]
Use of nanomaterials for improving the shelf life of harvested crops	Silver nanoparticles (AgNPs)	Cavendish banana	Reduced spoilage and increased storage time	Limited research on the efficacy and safety of nanomaterials for food applications	Further research on the efficacy and safety of nanomaterials for food applications, including their potential impacts on human health	[25]

utilizing fewer resources and avoiding environmental collateral damage. Table 1 summarizes the various nano-enabled strategies for crop improvement, underlying challenges, and future implications. The following section of the review will focus on the potential applications of ENMs in sustainable agriculture, with a specific emphasis on enhancing stress resilience in crop plants.

2.1. Nanofertilizers for efficient utilization of agrochemicals

Nano-based strategies could help in improving fertilization for enhanced plant growth and development by several ways including direct uptake of nano-scale nutrients, targeted delivery of nutrients for efficient utilization, and slow nutrient release strategy [26]. There are several types of synthesized nanoparticles, but AuNPs and AgNPs are

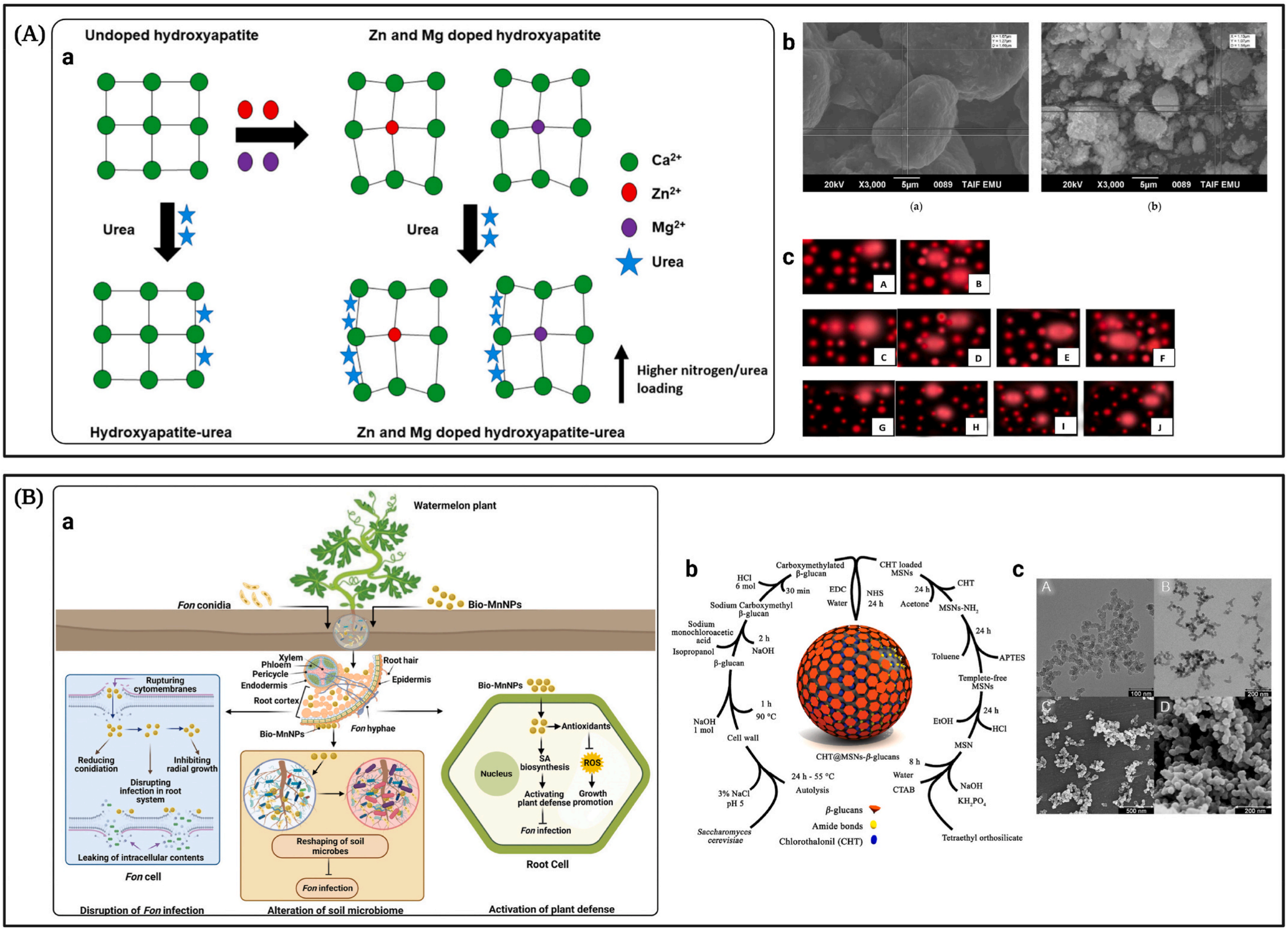

Fig. 2. Synthesis and application of ENPs as nanofertilizers and nanopesticides.
(A-a). Schematic diagram of Zn- and Mg-doped hydroxyapatite NPs fabricated with urea as slow nitrogen-releasing nanofertilizers. Adapted with permission from Sharma et al. [46], Copyright 2022 American Chemical Society. (A-b). 3000× magnified Scanning Electron Microscope (SEM) images of phosphorous-containing hydroxyapatite nanoparticles synthesized by using pomegranate peel (nHAPs_PPE) and phosphorous-containing hydroxyapatite nanoparticles synthesized by using coffee extracts (nHAPs_CE); showing their crystalline structure. (A-c). Photomicrographs of *P. granatum* EtBr-stained protoplast DNA treated with nHAPs where A: control; B: NPK; C–F:50, 100, 500, and 1000 ppm concentrations of nHAP_PPE. Adapted with permission from Abdelmigid et al. [47], Copyright 2022 Multi-disciplinary Digital Publishing Institute.
(B-a). The application of bio-MnNPs for suppressing Fusarium wilt by the disruption of *Fon* infection in watermelon, activating the defense mechanism and modifying the soil microbiota. Adapted with permission from Noman et al. [48], Copyright 2022 John Wiley and Sons. (B-b). Steps for the synthesis of CHT@MSNs-β-glucans. (B-c). High-resolution TEM images of A: MSNs and B: CHT@MSNs-β-glucans. SEM images of gold dust coated C: MSNs and D: CHT@MSNs-β-glucans. Adapted with permission from Kaziem et al. [49], Copyright 2021 American Chemical Society. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

most frequently employed due to their simplicity in preparation, bio-conjugation, and promising results under various experimental conditions, but the use of heavy metal nanoparticles in nano fertilizers is not primarily to fulfill the nutritional needs of plants, but rather for their unique properties and potential benefits in enhancing plant growth and nutrient uptake [27]. The development of NPs that are tailored to the needs of various plant-related processes has been accomplished; based on the use of different metals (Zn, Ag, Cu, Fe, Au, and Ni) and metal oxides (Al_2O_3, SiO_2, TiO_2, CeO_2, Fe_2O_4, etc.) [28–30]. The application of nanoscale iron is reported to significantly increase the germination, chlorophyll content and other physiological parameters in rice and maize [31]. Furthermore, Larue et al. (2018) have examined that the leaf spray of TiNPs at optimum concentration may upregulate the plant's photosynthetic efficiency along with other physiological activities [32]. ZnNPs significantly encourage the germination of seeds in a wide variety of crops, for example, wheat, onions, peanuts, and soybeans [33]. Moreover, Ashfaq et al. applied copper carbon nano fertilizers (Cu-CNFs) on chickpea and found that they translocated much efficiently through the roots to shoot to leaves. Cu-CNFs were capable of releasing Cu ions in a controlled manner within the plant. By increasing the water uptake capacity, germination rate, chlorophyll and protein content, the Cu-CNFs ensure high nutritional content and encourage growth of the plants [34]. An alternative study involves encapsulating Cu–Zn-CNFs in polymeric composites of starch and polyvinyl alcohol. The resultant Cu–Zn-CNFs composites facilitated the growth of plants [35]. A significant improvement is also observed in plant growth and nutrition quality because of graphene and GO-based carbon materials. According to Jiao et al. graphene oxide-treated plants exhibited shortened seminal roots, whereas a higher number of adventitious roots was also observed [36]. Graphene quantum dots synthesized by Chakravarty et al. were observed to affect the growth of garlic and coriander plants by improving leaf, shoot, root, flower, and fruit growth [37]. Nanomaterials can also minimize the loss of fertilizers through infiltration and runoff by releasing them in a slow and sustained manner. Liu et al.

has discussed that, in comparison to traditionally used water-soluble phosphorus fertilizer, synthetic apatite NPs sustained the bioavailability of soil phosphorus by reducing its mobility, resulting in an enhanced yield (20.4%) and growth rate (32.6%) of soybean [38]. According to Mikhak et al. an increase in availability and longevity due to the slow release of phosphate by the application of surfactant-modified zeolites [39]. A nanoscale formation of such nutrients as copper in the form of $CuO_{(s)}$, and iron as $Fe(OOH)_{3(s)}$ can be applied directly to the plants for enhancing plant growth [11,40]. The advantages of using these nanoscale fertilizers have been discussed extensively in the literature; for example, use of nanoscale micronutrients is also associated indirectly with the enhancement of macronutrient uptake [41,42]. Field studies, though limited, have suggested the low doses of nanoscale micronutrients to be responsible for overcoming abiotic stress conditions by boosting crop growth [43]. Nanoscale fertilizers can be applied either as aerosols or aqueous suspensions, as reported in lab studies [44, 45] According to Sharma et al. a two-step method of synthesizing three different variants of nanohybrids hydroxyapatite-urea, Zn-doped hydroxyapatite-urea and Mg-doped hydroxyapatite-urea to be used as slow-releasing nitrogen fertilizer as shown in Fig. 2(A-a). It is evident from the results that nanohybrids with 50% nitrogen doses maintained the nitrogen uptake efficiency and yield of wheat crop equivalent to the urea fertilizer with 100% nitrogen doses, which is a way-forward to mitigate ammonia from the agriculture fields [46]. Similarly, Abdelmigid et al. demonstrated the fabrication of phosphorus containing hydroxyapatite NPs (nHAP) using coffee ground extracts and pomegranate peel, thereby suggesting a novel green synthesis approach for the synthesis of phosphorus nanofertilizers. Fig. 2(A-b and A-c) shows the SEM images and photomicrographs of fabricated NPs [47].

The role of nanoscale fertilizers on plant growth and productivity has been studied at lab scale, greenhouse, and field levels. Therefore, the technology readiness level for this strategy tends to be relatively higher as micronutrients are needed in trace amounts that can be managed well compared to macronutrients which are needed in large amounts for field-scale applications. However, the impact associated with the application of nanoscale micronutrients is also lower as compared to macronutrients.

2.2. Nanopesticides for enhanced control efficacy of plant pathogens

In order to ensure the sustainable production of crops, it is particularly important to minimize crop losses caused by various pathogens, pests, and environmental stresses. Nano-enabled pesticides can help in achieving these endeavors. According to an estimation, the global pesticides market tends to grow from US$75 billion (in 2013) to US$90 billion (by 2023) [50,51]. The probability of pesticides reaching their targeted site when applied to the field could be as low as 0.1% [52]. Nano-formulations can improve this accuracy to a new level by assisting in the targeted delivery of pesticides. Savi et al. investigated the effectiveness of zinc compounds in preventing wheat Fusarium head blight and deoxynivalenol production [53]. Pre-sowing seed application with metal nanoparticles (Zn, Ag, Fe, Mn, and Cu) resulted in the development of the defensive response in wheat seedlings infected with *Pseudocercosporella herpotrichoides* [54].

Plant pathogenic fungus such as *Bipolaris sorokiniana* (common root rot, leaf spot disease, seedling blight, head blight, and black point of wheat and barley) and *Magnaporthe grisea* (rice blast) have been reported to be suppressed by several kinds of silver ions and nanoparticles [55]. The fungus invasion was greatly reduced by the NP treatments. For *B. sorokiniana*, the effective concentrations of AgNPs in suppressing colonization by 50% (EC50) were higher than for *M. grisea*. The results of the above-mentioned researches imply that AgNPs can suppress certain pathogens; however, the outcomes varied and depended on the concentration and type of AgNPs used [56]. Chitosan is crucial to induce resistance in different crops. Noman et al. revealed the impact of bio-functionalized MnNPs in suppression of Fusarium wilt in watermelon through the disruption of *Fon* infection, triggering of host defense mechanism, and modulation of soil microbial community as represented in Fig. 2(B-a). Bio-MnNPs at 100 μg mL^{-1} resulted in an increased Mn content in the roots/shoots of watermelon, leading to improved growth and suppressed Fusarium wilt by inhibition of *Fon* infection process. Site-specific pesticides delivery is imperative to control fungal attack [48]. Kaziem et al. proposed an enzyme-responsive β-glucanase nano-delivery for modulating the chlorothalonil (CHT) in plant vascular system, thereby synthesizing CHT@MSNs-β-glucans by the attachment of β-glucans from yeast cell walls with the MSNs pore rims, to control *M. grisea*. The synthesis pathway of CHT@MSNs-β-glucans and its characterization using SEM and HR-TEM imaging is shown in Fig. 2(B-b and B-c). Results showed that CHT@MSNs-β-glucans had 24.99% loading efficiency, outstanding dependency over enzymatic release, protection from acidic and alkaline environment, 3 times better UV shielding and enhanced bioactivity against rice blast, compared to CHT commercial product (CHT-WP) [49]. Chitosan has emerged as the material of preference for the creation of nanoparticles in a range of fields because of its sustainable and harmless qualities [57]. For example, *Aspergillus niger*, *Alternaria alternata*, *Rhizopus oryzae*, *Phomopsis asparagi*, and *Rhizopus stolonife* all have been found to be resistant to the fungal effects of chitosan in its free polymer type [58]. Similarly, Cu-chitosan nanomaterials have been tested for their ability to promote plant growth and enhance systemic resistance against the *Curvularia* leaf spot disease of maize [59]. Now, nano-pesticides are at a ready-to-use stage and present a viable solution for sustainable crop production. Further research is needed to characterize the new materials in terms of sophistication such as selectivity and lack of responsiveness to environmental triggers. Although the currently used products like Kocide 3000 have no such concerns, however, the infield delivery of nanomaterials is subjected to challenges such as the possibility of alteration in the structure of nano-formulations by in-tank pressurization, such factors need to be carefully assessed and managed accordingly. Nanomaterials are being explored for improved pesticide efficiency, targeted delivery, and controlled release in agriculture. However, the potential uptake of nanopesticides by plants, and their subsequent impact on plant health and food safety, is a subject of research and concern, prompting the need for thorough investigation and risk assessment to ensure safe and sustainable use while mitigating adverse effects on plants, ecosystems, and human health.

2.3. Nano-sensors for improved precision farming

The automation of agricultural practices has proved to be fruitful by ensuring efficient crop management and environmental compatibility with minimum manpower [60]. The plant nano-sensors can pave way for farmers to communicate with the plants hence ensuring plant protection and sustainability [61]. Plant-integrated nanoparticles can be used for the detection of specialized signaling molecules associated with stress and nutrient deficiencies, transforming them into electrical or optical signals in the detection devices. Nano-biosensors, global navigation satellite systems, and global positioning systems are some of the nano-based devices used for automated assessment of the nutrient balance, stress levels, and health status of plants. This has enabled a single-handed control over multiple agricultural projects without involving physical inspection [62,63]. The real-time monitoring of plant health enables efficient resource management prior to the loss thus contributing to significant survival and growth enhancement. It has paved the way towards sustainable agriculture with better control over resource management, soil health, crop improvement via genetic engineering, calculated supply of agrochemicals such as fertilizers, etc. [10, 64]. Nano-sensors have become an eminent tool to detect, track and overcome pathogen attacks in plants. They can detect a wide range of targets including pathogens, pesticides, herbicides, insecticides, fertilizers, soil pH, moisture, etc. They are also used to monitor rhizosphere soil health by detecting different gases, trace heavy metals,

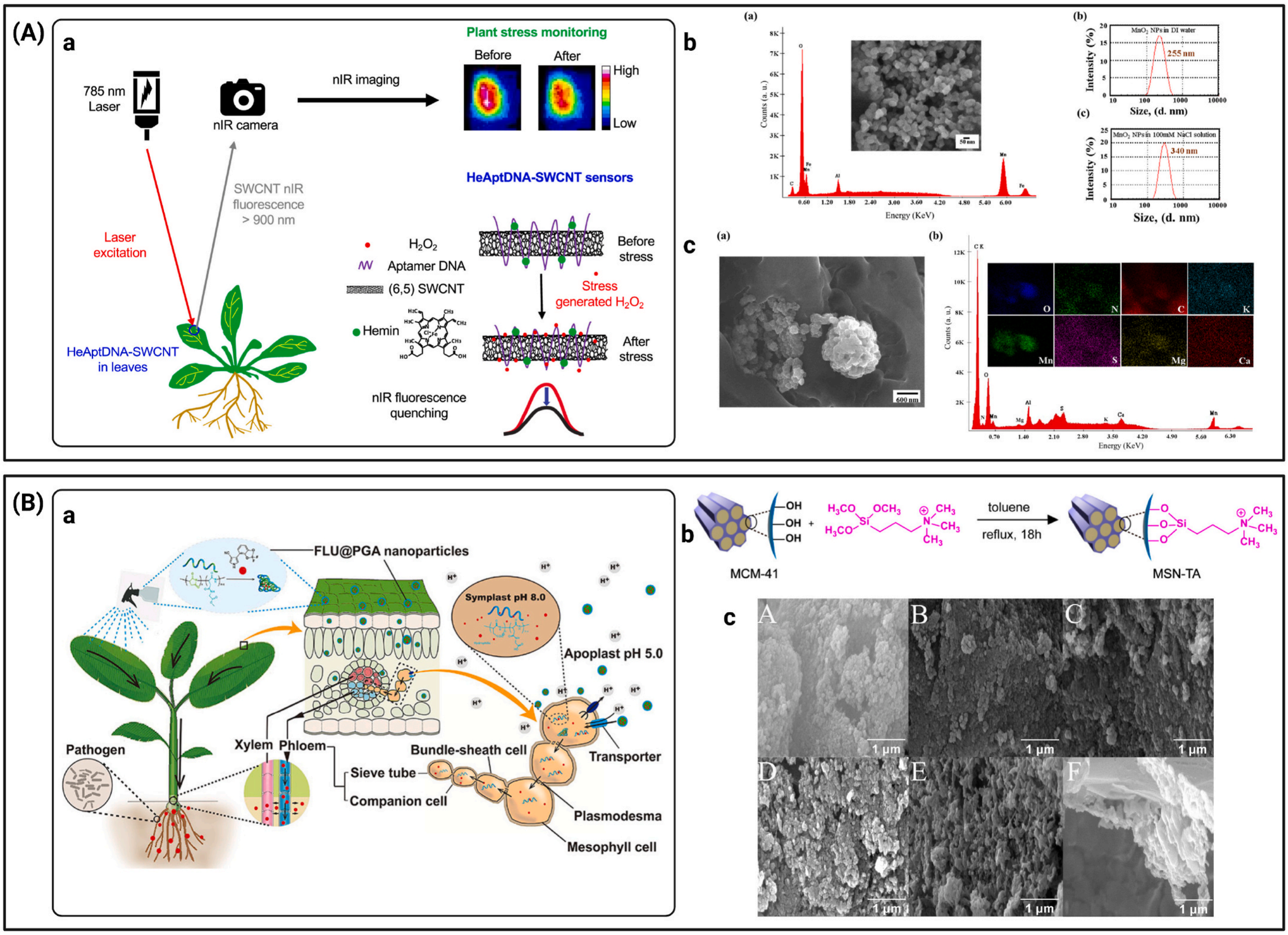

Fig. 3. Synthesis and characterization of ENPs as nano-sensors and nano-carriers.
(A-a). Use of SWCNT sensors for *in vivo* monitoring of H_2O_2 to examine plant health through remotely recording the spatial and temporal modifications in the intensity of near-infrared fluorescence in leaves with HeAptDNA-SWCNT using a near-infrared camera. Adapted with permission from Wu et al. [68], Copyright 2020 American Chemical Society. (A-b). a: SEM and EDS results of MnNPs; b–c: Dynamic light scattering results of MnNPs (1 mg/L) in Milli-Q water and NaCl solution (100 mM), respectively. (A-c). a: SEM image of MnNPs in primed seeds of *C. annum*; b: EDS spectra and mapping results of O, N, C, K, Mn, S, Mg, and Ca. Adapted with permission from Ye et al. [69], Copyright 2020 American Chemical Society.
(B-a). Schematic representation of fludioxonil delivery in phloem mediated by amino acid transporter-mediated polysuccinimide nanocarriers to regulate Fusarium wilt in banana. Adapted with permission from Wu et al. [73], Copyright 2021 American Chemical Society. (B-b). Synthesis process of MSN-TA nanocarriers. (B-c). SEM (A, B) and TEM (C, D, E) images of TA functionalized MSN. Adapted with permission from Cao et al. [74], Copyright 2017 American Chemical Society.

micronutrients, etc. The resulting data helps to protect crops against pathogenic diseases and boost yield by providing the right nutrition to the soil [65,66]. The proper utilization of nano-sensors can result in an augmented crop production thus facilitating the farmer [67]. This is a step forward toward precision farming, turning traditional agriculture into smart, cost-efficient, and sustainable agriculture.

Most of the nanotechnology-based plant sensors associated with the electronic devices have been tested in the lab environment with controlled conditions. Wu et al. designed near-infrared fluorescent single walled carbon nanotubes (SWCNTs) functionalized with DNA aptamer that interacts with hemin (HeAptDNA-SWCNT) and applied to *Arabidopsis thaliana* leaves to monitor H_2O_2, a key signaling molecule associated with the onset of stress in plants as shown in Fig. 3(A-a). These sensors were found to report early symptoms of stress in plants and are useful for remote monitoring of plant health [68]. Ye et al. investigated MnNPs as nano-priming agent to lessen the salinity stress in *Capsicum annum* at the time of germination supplemented with 100 mM NaCl. Scanning Electron Microscope (SEM), energy dispersive spectroscopy (EDS) showed penetration of MnNPs across the seed coating to form complex of NPs with biological molecules (Fig. 3(A-b)). Similarly, dynamic light scattering revealed that the hydrodynamic size of MnNPs was larger in NaCl (340 nm) as compared to when dissolved in Milli-Q water (MW) (255 nm). SEM image revealed the formation of clusters by MnNPs while penetrating the seed coat during priming. As, C, N, O, and S are the most important elements in proteins, elemental mapping therefore depicts an interaction between MnNPs and proteins (Fig. 3 (A-c)) [69]. Lately, the nanomaterials with plasmonic properties were combined with smartphone fingerprinting to diagnose plant diseases non-invasively in the lab and greenhouses. The transformation of plants into detectors resulted in the significant improvement of agricultural sustainability [70]. Although the wide adaptation and emerging interest in the use of intelligent nano-sensors in modern-day agriculture for observing crop and soil health, the accuracy and practical field application of such products are yet to be optimized [71]. The practical testing of such devices in the phenotyping facilities and natural agricultural environments, subjected to fluctuations in weather conditions, plant growth, development patterns, etc. is yet to be validated [72]. Therefore, intensive research is needed to contribute toward sustainable agriculture by using nano-sensors.

2.4. Nanocarriers for the effective delivery of biomolecules

In addition to delivering genetic information to plants to enhance gene editing, nanotechnology permits stabilizing genetic materials like dsRNA to improve its effectiveness as an agent for pest control. With the advent of advanced genetic engineering techniques like CRISPR-Cas9, the possibility of improving crop yield and resistance has increased enormously. However, the delivery of foreign material into plant cell across the cell wall is still a challenge in implementing such techniques in plant biotechnology. Nanomaterials can play a key role in grafting and targeted delivery of desired exogenous biomolecules for genome editing [75]. Similarly, the incorporation of foreign DNA in the plant can be replaced by the DNA plasmids delivery that code for the CRISPR resulting in a controlled expression of Cas9 via non-biolistic and non-pathogenic method [76]. The application of nanocarriers in agriculture can lead to drastic changes in the way of crop improvement [77,78]. However, there are only a few studies that discuss the delivery of nanomaterials across the plant cell wall [79]. In-depth research is needed to understand the impact of engineered nanoparticles on plant physiology and how affect their ability to internalize the plant cells by changing the size, shape, tensile strength, and aspect ratio as well as the physicochemical properties and characteristics of these nanomaterials.

Wu et al. demonstrated the fludioxonil (FLU)-loaded glycine methyl ester-conjugated polysuccinimide (PGA) NPs (FLU@PGA) has the capability of pH sensitive controlled release in plant phloem under alkaline conditions. It is found to mitigate the disease intensity by 50.4% in banana through the targeted delivery of FLU to the roots and rhizome after foliar application of FLU@PGA. The mechanism of action of FLU@PGA is demonstrated in Fig. 3(B-a) [73]. Furthermore, Cao et al. used post-grafting process to synthesize positively charged functionalized mesoporous silica NPs (MSN-TA) by incorporating trimethylammonium groups (TA) as shown in Fig. 3(B-b and B-c). The loading efficiency greatly improved to 21.7% compared with bare MSNs having 1.5%. It was evident from the results that MSN-TA can mitigate soil leaching of 2,4-D sodium salt. Furthermore, there were no adverse effects found on the nontarget plants with the use of this nanoformulation [74]. This strategy of using electrostatic interactions, is a potential solution for the delivery of charged agrochemicals without adverse non-target effects. Resistance against several pests and pathogens can be developed in transgenic crops through the production of dsRNA. High-sequence complementary RNA is silenced by the single-stranded small interfering RNA (siRNA), produced by the enzymatic processing of the dsRNA in plants [80,81]. The topical application of dsRNA to prevent viral and pest attacks on leaves, presents an alternative to transgenic RNAi, as genetically modified crops, have regulatory and acceptance issues [82–84]. The impact of dsRNA-based pathogen protection is often short-lived due to its instability on the surface of leaves, but it could be solved with the use of nanomaterials that binds the exogenous dsRNA to make it stable, helps prevent degradation, and ensure successful release on the target site [78]. The effectiveness of using layered double-hydroxide (LDH) clay nanosheets with positive charge as the dsRNA nanocarriers is well-documented. LDH nanosheets are capable of binding large loads of dsRNA and facilitating the attachment with the surface of the leaf. LDH nanosheets are decomposed by the carbonic acid produced from the humidity and CO_2 on the leaf surface which leads to the sustained release of bound dsRNA. The LDH-assisted topical delivery of dsRNA results in a minimum of three times longer protection against the virus in comparison to the naked dsRNA [85].

The effectiveness of dsRNA is limited to certain taxa, specifically nematodes, and coleopterans (beetles) while leaving some important taxa such as lepidopterans (moths and butterflies). This is due to the absence of certain cellular machinery that allows the processing of dsRNA to siRNA by entering the cytoplasm while escaping the endosomes. To solve this, nanocarriers engineered with positively charged polymers have been employed that bind the dsRNA and also help it to reach the cytoplasm by penetrating the cell membrane [86].

The efficacy of the nanocarriers to enhance RNAi through the exogenous application of dsRNA is high and can be readily used. Nanocarriers also reduce the expense of dsRNA by reducing the amount of required dsRNA for successful treatment. Low-cost biopolymers like chitosan are the key players in this regard with the added benefit of being biodegradable. The application of this technology in the field of agriculture can overcome the concerns of genetic engineering and the adverse effects that accompany the application of pesticides with low accuracy [87]. Nano-assisted genetic manipulation is a way forward to sustainable crop improvement yet the long-term effects of the use of nanocarriers and their cargo on the environment are under consideration.

There are several synthetic nanocarriers used for delivering protein, DNA, and RNA that do not biodegrade. Contrary to this, nanocarriers used for the delivery of pesticides, macronutrients, and non-actives are generally biocompatible and biodegradable [80]. The technology readiness level of biodegradable nanocarriers is much higher in contrast to their non-biodegradable counterparts as their bioaccumulation can be an environmental concern.

3. Mechanism underlying nano-enabled sustainable crop production

The integration of nanotechnology in agriculture holds great promise for sustainable agricultural production, food security, and environmental resilience [88]. One significant nanomaterial in this context is carbon dots (CDs), which possess unique properties such as tunable photoluminescence, biocompatibility, and negligible toxicity. CDs have demonstrated remarkable biocompatibility, making them safe for agricultural application. Their potential as growth enhancers stems from their ability to augment photosynthesis and improve solar energy utilization, resulting in increased crop productivity. Furthermore, CDs' hydrophilicity accelerates seed germination and water absorption by plants, positively impacting plant growth. Their antimicrobial and antioxidant properties further contribute to plant health by alleviating biotic and abiotic stresses. CDs also find applications in agricultural sensors, enabling the detection of herbicides and pesticides, supporting the development of smart sensors [89]. Additionally, nanotechnology extends its benefits to horticulture, improving productivity, shelf-life, and quality of fruits and vegetables. Nanofertilizers, nanopesticides, and nanosensors provide targeted and efficient solutions for enhancing growth, fertility, and disease monitoring in crops [90]. Another area of interest lies in the role of polyamines (PAs) as vital bio-stimulants for plant growth and stress tolerance. Understanding the molecular complexity of PAs signaling in plants offers opportunities to improve crop stress resistance and yield [91]. Additionally, the effects of zinc oxide nanoparticles (n-ZnO) on alfalfa under heat stress revealed that foliar application of 90 mg L−1 n-ZnO before heat stress better prevents heat-induced damages and maintains superior plant growth and morpho-physiological attributes compared to post-treatment application, suggesting it as an effective strategy to protect alfalfa from heat stress damages while reducing environmental risks associated with nanoparticle transmission [92]. Nanotechnology also exhibits great promise in inhibiting plant pathogenic bacteria and fungi through metal-based nanoparticles' antimicrobial properties [93]. Fritillaria imperialis effectively survives freezing stress by activating tolerance mechanisms, including the upregulation of Ca2+ signaling proteins, NHX1, LEA, and P5CS, and the overexpression of OsCNGC6, resulting in enhanced Ca2+, Na+, and K+ accumulation to maintain ionic homeostasis, while antioxidant systems, like SOD, phenols, anthocyanins, catalase, and ascorbate peroxidase, are activated to counteract the high accumulation of H2O2 caused by freezing stress, leading to protection against water stress, oxidative stress, and photosynthetic damage during freezing stress [94]. Furthermore, nanomaterials, specifically carbonaceous nanomaterials (CNMs), have opened avenues for tissue regeneration in biomedical applications [95]. Nanopesticides offer a more efficient and sustainable approach to pest control with reduced environmental impact, supporting global food security. However, further research is needed to understand potential adverse effects of some nanopesticides [88]. The integration of nanotechnology in agriculture represents a transformative approach with far-reaching benefits for enhancing productivity, quality, and resilience in the face of evolving challenges.

3.1. *Promotion of plant growth*

There is a major economic loss in the field of agriculture due to environmental stresses like heat, drought, frost, and salinity. Climate change is leading to drastic effects in crop production by increasing the intensity and occurrence of stresses that pose a greater threat to sustainable crop production [96]. Various nanomaterials have been used to regulate this impact of environmental stresses thereby facilitating the growth and photosynthetic efficiency of the plants [97,98]. Cerium oxide NPs have been reported to enhance the photosynthetic efficiency of plants by reducing the accumulation of reactive oxygen species under stress conditions [99,100]. Moreover, AboDalam et al. have described that the pre-germinated wheat seeds, soaked in a solution containing multiwall carbon nanotubes (MWCNTs), have accelerated root development and increased vegetative biomass [101]. The treatment of soybean seeds with NPs of TiO_2 and SiO_2 increased nitrate reductase activity, which stimulates seed germination; however, combined application of both NMs was more beneficial [102]. Similarly, soaking watermelon seed in Fe_2O_3 nanoparticles improved germination, sparked plant growth, and induce fruiting [103]. Furthermore, Szőllősi et al. have described that the Indian mustard's uniformity, rate of germination was improved, as well as its root and shoot growth was accelerated, by soaking seeds in an oxidized MWCNT solution [104]. Mesoporous silica NPs also facilitate the seedlings to grow via photosynthesis enhancement when delivered through the nutrient media where they travel from the roots to shoots and settle in the chloroplast to function [10,105]. Moreover, Feng et al. have demonstrated that the seed treatment with 0.25% of TiO_2 nanoparticles increased the rate of photosynthesis and nitrogen uptake, which have increased the dry weight of spinach up to 44% as compared to control [106]. Similarly, McGehee et al. have described that carbon nanotubes directly applied to the leaves can promote photosynthetic activity and facilitate the growth and yield when applied hydroponically in tomato plants [107]. There are still concerns about the safety of carbon nanotubes from the environmental perspective which needs to be validated for field applications. Moreover, Pereira et al. have explained that plant hormones can also be delivered by the nanocarriers. In common bean plants, gibberellic acid delivered by the chitosan and alginate NPs tends to broaden the leaf area and enhance chlorophyll content [108]. Sun et al. have demonstrated that the plant stress responses can also be improved by the delivery of abscisic acid and salicylic acid mediated by the mesoporous NPs with accompanying controlled release redox-responsive channels [109].

The impact of nano-based seed coating strategy on the agrochemical industry is not well-studied to make a claim about its technology readiness level. Similarly, the advantages associated with the technology are also not reported rigorously, therefore it is difficult to assess the benefits comprehensively. According to recent studies, the use of biosynthesized AgNPs coatings [110] and cobalt NPs coating [111] mediated by electro-spun show promising potential for improving germination efficiency. Compared to other Zn forms, the use of Zn as ZnO had a more noticeable impact on the growth of tobacco callus and physiological indices. When those were given to the callus as NMs, they accumulate more Zn. In addition to encouraging callus growth, this led to higher protein contents [112,113]. In cluster bean chlorophyll, total soluble leaf protein, and phosphorus concentrations were increased after foliar application of ZnO NPs [59]. Compared with the traditionally employed zinc supplements, the use of ZnO-NPs coated with dextran in Triticum aestivum (wheat), depicted and enhanced Zn content and growth performance [114]. Nanomaterials have also been found to be very effective in enhancing plant growth through quicker and better seed germination as well as increased capacity for fertilization [115]. By maintaining the effective quantum yield of cyclic electron flow during photosynthesis and photoprotection, foliar application of SiO_2 nanoparticles improved sugarcane growth under chilling stress [116] Generally, the practical advantages of nano-enabled seed coatings and macronutrients are relatively higher by improving germination rate, plant growth, and subsequent resistance against pathogens, therefore, further studies should be carried out to elucidate the promoting mechanism of nanomaterials and their impact on plant yield and growth through transplant facilities or field-scale trials.

3.2. *Reshaping of plant microbiome*

Nanomaterials have the potential to improve soil characteristics thereby improving the productivity and sustainability of agriculture by enhancing the nutrient uptake, optimizing water holding capacity, and protecting against plant pathogens [117]. The importance of plant-microbe interaction is well-known in the agriculture sector [118]. For instance, the regulation of soil and Phyto-microbiome led to the enhanced tolerance against saline irrigation waters and assisted in the suppression of diseases [119,120]. Studies have reported the role of nanomaterials such as CuO, Ag, and TiO_2 in modifying the soil microbial community leading to the regulation of key features of soil and plants as shown in Table 1. Carbon and carbon-based nanomaterials have diverse applications in the plant system, as they exhibit size, concentration, and solubility-dependent penetration into roots and further to shoots, resulting in significant changes in plant metabolic functions, increased biomass, and improved fruit production and grain yield. These nanomaterials also demonstrate the ability to enhance seed germination, plant growth, photosynthetic efficiency, and the production of metabolites, including medicinally relevant compounds. Under stress conditions, multi-walled carbon nanotubes and graphene-based nanomaterials show a promotive effect by mitigating the adverse impacts of salinity and drought on various plant species. Additionally, they have been used as antifungal agents through the encapsulation of fungicides. However, while carbon-based nanomaterials influence soil microorganisms, their effects on soil microbial communities can be both beneficial and adverse, thus warranting a careful assessment of their mechanisms of action in the rhizosphere, plant growth, development, and protection against diseases [121]. According to Zhang et al. the use of AgNPs, CuONPs, and ZnONPs can affect the soil microbiome at a high dose of 100 mg/kg, while no considerable change was observed at a dose of 10 mg/kg and 1 mg/kg [122]. In contrast to this, Ge et al. have found that even a dose of 100 mg/kg could not alter the composition of the soil microbiome in the case of TiO_2 NPs, suggesting the different impacts of specific NPs [123]. There are a limited number of studies that discuss the role of nanomaterials to engineer soil or Phyto microbiomes. Asadishad et al. have stated that the dynamic nature and complexity of soil properties due to associated microbial communities are other challenges in the way of practical implementation of this approach [124]. Considering this, the technology is yet difficult to be declared as ready to use, however, its role in sustainable agriculture is certainly important.

3.3. *Improvement of soil quality*

Soil improvement can lead to a valuable increase in crop production and food quality particularly in the areas affected by soil degradation and environmental stresses. Traditional soil conditioning practices in agricultural lands are not based majorly on nanotechnology even [125–127]. However, there are several nanomaterials that can be used for soil conditioning [128,129]. Moreover, Liu et al. have examined the

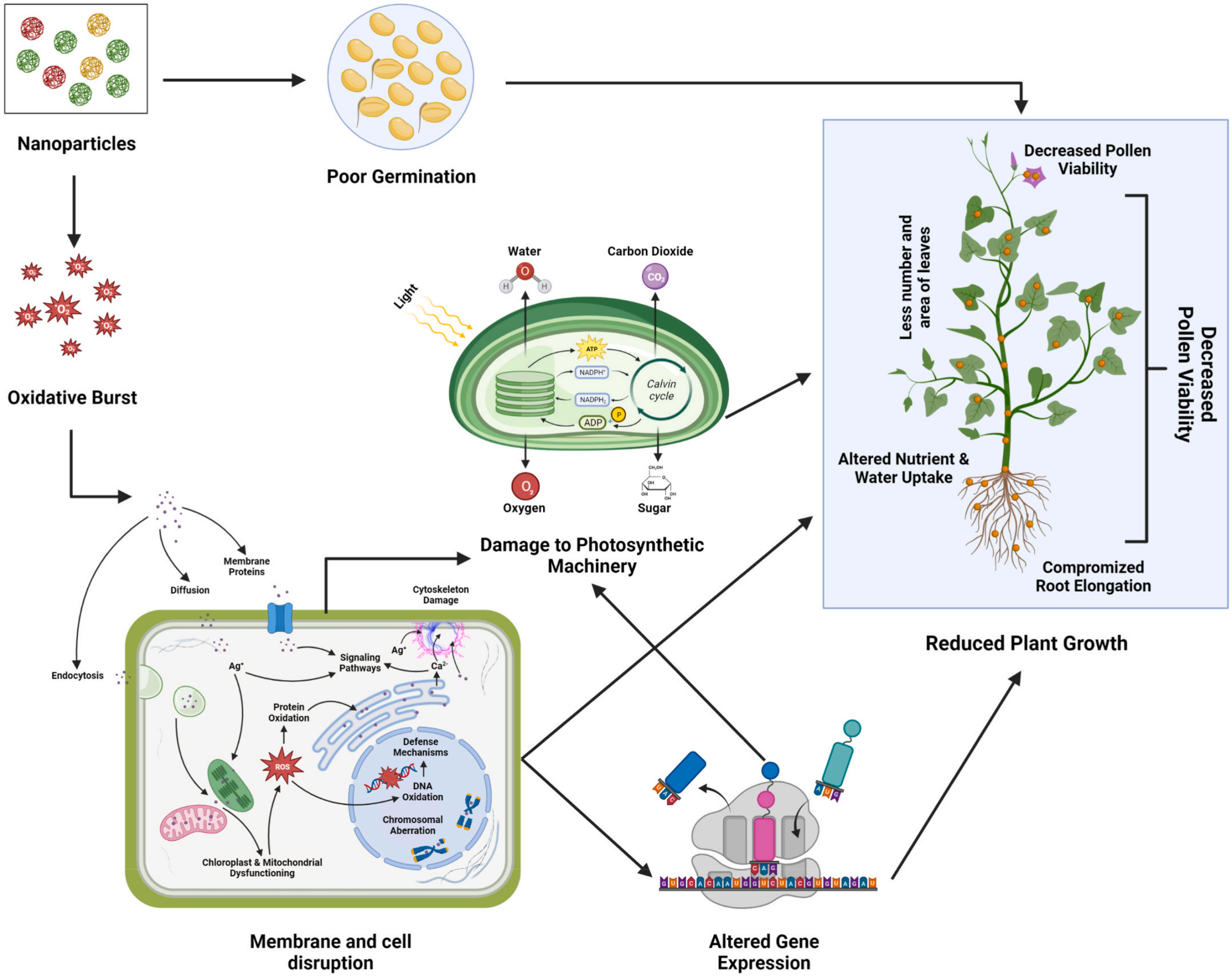

Fig. 4. Nano-toxicity of ENMs on crop plants by inducing physiological, biochemical, and molecular responses. Nanoparticles can lead to poor seed germination, cause oxidative burst, damage to photosynthetic machinery, alter the gene expression and reduce the overall plant growth by decreasing the pollen viability, compromising the root elongation, reducing the leaf number and surface area, as well as by altering the nutrient uptake. This figure is created by using BioRender (https://biorender.com/).

hydrothermally produced nano-based mineral soil conditioner derived from potassium-rich feldspar and have found its roles in elevating soil pH, improving soil density, and mitigating the aluminum and cadmium toxicity in the crop [130]. Furthermore, Kiran et al. have suggested that water retention capacity was improved by using biodegradable cross-linkers [131]. The wheat crop yield can be enhanced along with the improvement in soil characteristics by using chitosan NPs [132]. However, all studies in this area are mostly conducted at a lab scale and lack estimations and feasibility assessments to produce these nano-based conditioners for field-scale applications [129]. Traditional methods for improvement in soil characteristics have been used for decades, it is hard to replace them with nanomaterials, primarily due to the need of large requirements in terms of amount and lack of opportunities in precision agriculture [133]. The technology is still in its infancy and large-scale feasibility testing would be needed to step forward.

4. Environmental concerns and nano-toxicity issues of ENMs

Despite numerous reports of NMs' positive effects, their application may also be phytotoxic, which depend on the concentration and type of ENMs used as well as exposure conditions and duration [134,135]. ENMs have been reported to inhibit seed germination, shoot growth, and root growth and decrease chlorophyll and photosynthesis concentrations in various crops including onion, spinach, radish, soybeans, coriander, barley, wheat, rice, lettuce, cucumber etc. [136–138]. Furthermore, Yusefi et al. found that smaller size CuO nanoparticles (25 nm diameter) were more phytotoxic to soybean [139]. Even though there is a considerable amount of conflicting information regarding the eco-toxicological effects of nanoparticles, most of the scientific studies indicate a mild to moderate toxicity for terrestrial plants [140,141]. Metallic nanoparticle exposure may lead to oxidative damage in plants, producing reactive oxygen species (ROS) and activating antioxidant defense mechanisms [142]. Ascorbate peroxidase, catalase, superoxide dismutase, guaiacol peroxidase, glutathione reductase, and other enzymatic and non-enzymatic antioxidants are all part of the antioxidant defense system that detoxifies free radicals [143]. To combat oxidative stress brought on by nanoparticles, plants have developed antioxidant capacity [144]. Several NMs activate the antioxidant enzymes, with Fe_2O_4, CeO_2, and Co_3O_4 causing catalase to be produced; Fe_3O_4, CeO_2, MnO_2, Cuo, and Au causing guaiacol peroxidase to be produced; and CeO_2, Pt, and fullerene causing superoxide dismutase to be produced [145]. The nanoparticles may inhibit seed germination, slow down plant

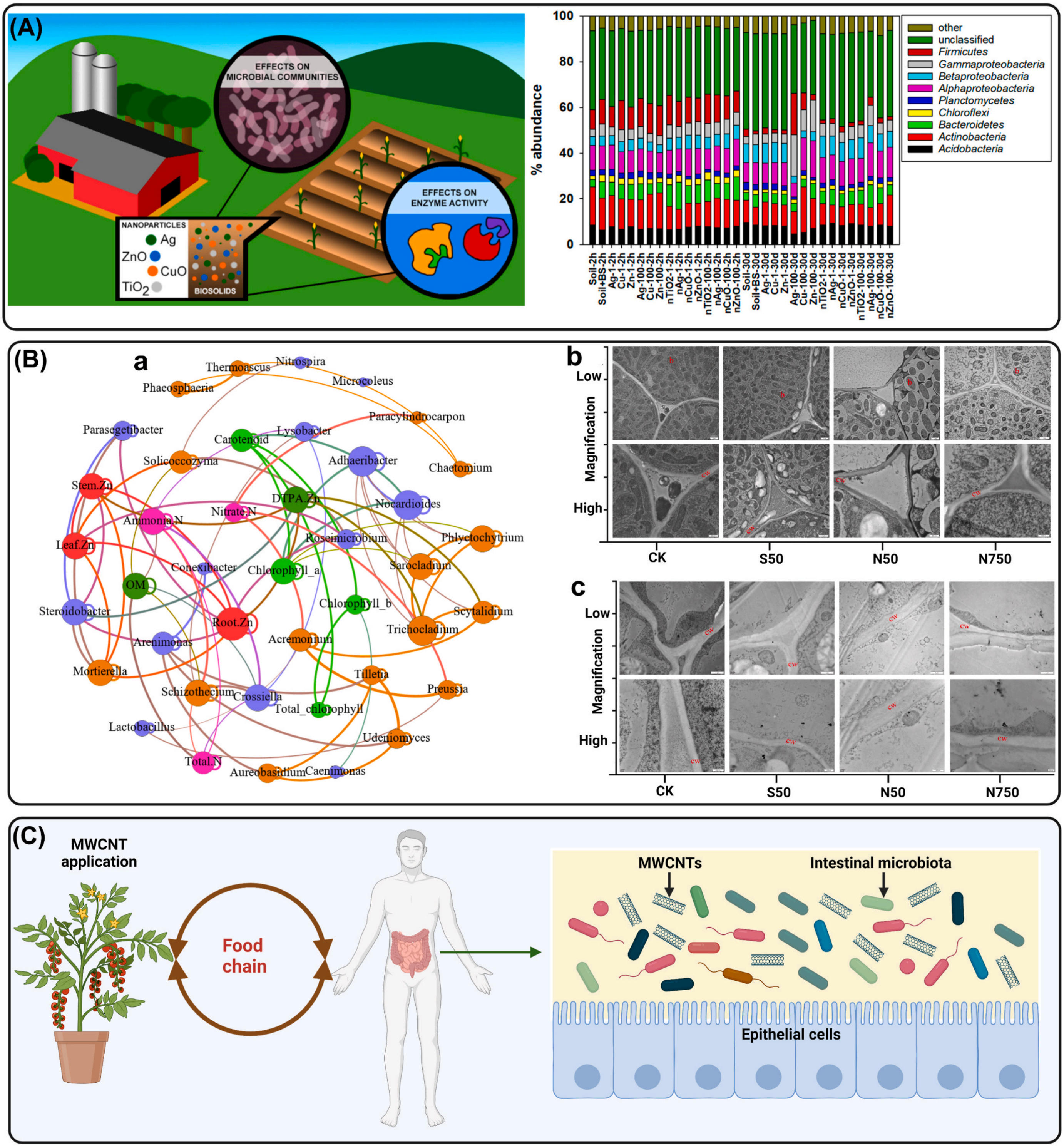

Fig. 5. Toxicity and fate of nano-agrochemicals in agricultural ecosystems and food chain.

(A) Amendment of agricultural soil with metal nanoparticles (ZnO, CuO, and TiO) affects microbial community composition. Adapted with permission from Asadishad et al. [124], Copyright 2018 American Chemical Society. (B-a) Effects of short-term soil exposure of different doses of ZnO nanoparticles on the plant associated microbiome. (B-b) Transmission electron microscopic (TEM) analysis of the ultrastructure of root nodule cells. (B-c) TEM analysis of the ultrastructure of the root cells Adapted with permission from Sun et al. [155], Copyright 2022 Elsevier. (C) Schematic diagram of the influence of carbon nanotubes (CNTs) on the human intestine microbiome once introduced into the food chain. Adapted with permission from Lahiani et al. [154], Copyright 2019 Royal Society of Chemistry.

growth and development, and occasionally even kill plants [146], which may be caused by inducing physiological, biochemical, and molecular responses such as damage of bio-membranes and genomic DNA, reduction in photosynthetic rate and plant growth hormones, chromosomal abnormalities, disruptions in the transport of water and the status of the plant's water supply, as well as changes in subcellular metabolism and genes expression [1,147,148]. By suppressing the transcription of genes, the use of fullerene nanoparticles disrupted the energy and electron transport pathways [149]. On the other hand, some nanoparticles increased the expression of numerous genes, including those

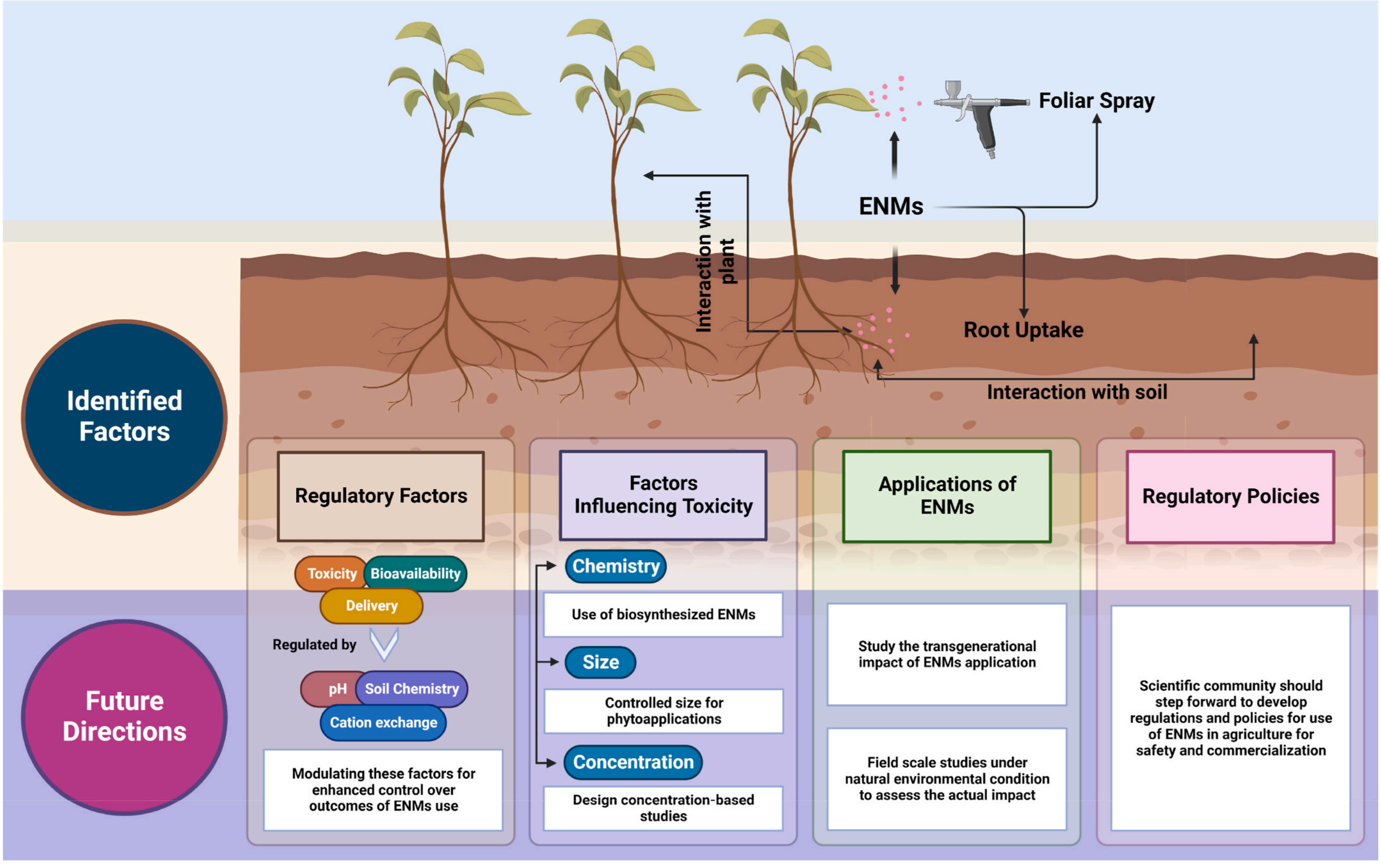

Fig. 6. Schematic diagram representing research gaps and key areas to focus on in future research targeting the use of ENMs in sustainable crop production. This figure is created by using BioRender (https://biorender.com/).

linked to stress and water channels [145]. The genes NNtPIP1, NtLRX1, and CycB, which regulate water transport, cell wall formation, and cell division, respectively, were upregulated by using MWCNTs [150]. The comprehensive overview of nano-toxicity of ENMs to crop plants is shown in Fig. 4.

ENMs are increasingly being used and concentrated in various environments, posing enormous environmental risks due to which they became the most difficult pollutant type to control [151]. The degree of toxicity of a nanoparticle depends on its solubility and specificity of binding to a biological site. The antimicrobial properties of ENMs of metallic nature could unleash a completely unknown cascade of changes in the communities of microorganisms in ecosystems [152] as shown in Fig. 5(A), which might be harmful to plants and humans. Despite the ease of degradation of CNMs, fullerene is preferentially consumed by fungi that decay wood. The fullerene NPs subsequently accumulate in microorganisms and are transferred further along the food chain because of feeding relationships. There is a possibility that, even if there is no acute toxic effect of these ENPs, long-term exposure to them may have unexpected impact on the food chain [153]. As per a recent study, Lahiani et al. have reported that the amount of carbon nanotubes that translocate from roots to shoots is low enough and has no impact on human microbiota and gut health, if consumed as shown in Fig. 5(C). The role of growth enhancers to protect plants against the abiotic stresses when delivered through the nanocarriers is still underway [154]. Carrier proteins (aquaporins), endocytosis, ion channels, and formation of completely new pores are all mechanisms through which these NMs enter plant cells. There is also an apoplastic and symplastic movement of NMs through xylem and phloem. Seeds, flowers, and fruits have a noteworthy tendency to collect ENPs, in relatively higher concentrations, from the phloem through sink activity. This brings up the issues of safety in the consumption of such plant products by humans and animals, in addition to the toxicological effects on the plant [140]. There is a possibility that they may enter the food chain in any of these situations and cause unanticipated consequences. Additionally, excess Fe_3O_4 NPs can cause oxidative stress in plant systems resulting in a decline in metabolic efficiency. A ZnO NPs may have a detrimental effect on chromosomal and cellular attributes and can be hazardous to health [141]. Moreover, effects of short-term soil exposure after applying different doses of ZnO nanoparticles on the plant associated microbiome is reported as shown in Fig. 5(B-a) and Fig. 5(B-b and B-c) represents TEM analysis of the ultrastructure of root nodule cells and TEM analysis of the ultrastructure of the root cells, respectively [155].

A few ENPs such as ZnO, SiO_2, and TiO_2 are photochemically active and are capable of generating superoxide radicals by direct electron transfer under light. Studies have shown that metallic ENMs trigger an oxidative stress in plants, inhibit ROS detoxification mechanisms, and cause plant genotoxicity in cultivated plants (such as wheat and tomato) [156]. Another study aimed to compare the toxicity effects of three carbon nanomaterials (C60, rGO, and MWCNTs) on a rice mini-ecosystem, observing negative impacts on rice shoot height and root length, as well as changes in root cortical cells, and increased concentrations of phytohormones and antioxidant enzymes in response to high exposure doses of CNMs, while minimal shifts in the predominant soil bacterial species were observed; these findings underscore the importance of careful management and regulation of CNMs to prevent potential risks to both living organisms and food safety in the environment [157]. Nevertheless, some studies have also shown that they can protect against oxidative stress. For this reason, mechanistic understanding of ENMs metabolism in organisms and specific cells needs to be investigated. It is also necessary to explore possible mechanisms of adaptation to the delayed effects of exposure to ENMs. There is a need to investigate bioaccumulation of ENMs in food chains and their interactions with other environmental pollutants, as they could negatively impact major plant processes thereby affecting agricultural sustainability.

It is very important to closely monitor the introduction of chemical ENMs or green ENMs into the field. NPs should only be used in agriculture after confirmation of their non-toxic nature for yield improvements and to solve critical issues. A polymeric ENM with a plant-based insecticide coating is a unique agro-product, which has been growing in popularity due to their non-toxic nature. To avoid undesirable consequences of microbial community change across ecosystems, it is also important to assess how NMs impact soil microbes to preserve soil health and ecosystems. ENMs can play a crucial role in the ecosystem functioning, as accumulation of these ENMs in treated soil may threaten the soil microbiota as well as associated trophic organisms [122].

Table 2
Challenges in large-scale implementation of nano-enabled strategies in agriculture.

Key challenges	Description	Research directions	References
Biocompatibility of ENMs with plants	Understanding the interactions between engineered nanomaterials (ENMs) and plants to optimize their performance.	Limited knowledge about the underlying mechanisms of plant-ENM interaction.	[158] [159]
		Need for in situ studies to enhance the use of nanomaterials for stress management in plants.	[160] [161]
		Physico-chemical parameters governing plant-ENM interaction and impact on microbial communities need to be elucidated.	[162] [163,164]
Delivery and fate of ENMs in plants	Efficient and precise delivery of ENMs to millions of plants in field conditions.	Challenges with non-specific soil addition of ENMs, leading to high embodied energy.	[165]
		Chitosan nanocarriers and viruses for targeted slow release of ENMs.	[166,167]
		Need for better designing strategies to improve foliar application efficiency and adhesion to plant leaves.	[165] [168]
		Weather stresses (heat, water, salt) interfering with ENM delivery require timely application and pH/temperature-responsive ENM engineering.	–
Regulatory issues and social acceptability of ENMs	Ensuring safety and building public confidence in ENM use in agriculture.	Development of safety and regulatory policies for ENM use on food crops.	[169] [170]
		Metal-based ENMs may be less toxic to plants at equivalent doses compared to their ionic counterparts.	[171]
		Assessing and regulating the deliberate increase of ENMs in plants for consumption to avoid nutrient dilution and potential risks.	[172]
		Complexities involving multiple ecological units, weather conditions, societal acceptance, and regulations in different regions.	[173,174]

5. Challenges in large-scale implementation of nano-enabled strategies

Several challenges have been proposed in the way of wide adoption of ENMs-based Agri-technologies. Indeed, nowadays, there is a huge research gap in understanding the plant-ENM interaction, while delivery of ENMs to the desired vasculature or organelle of plant is another challenge, which is restricted by limited available options, lastly, the impact of deliberately applied nanomaterials on the plant health, soil, environment and indirectly on human health through plant-based food products is not clear yet as shown in Fig. 6. Furthermore, the adaptability of new technologies strongly relies on the feasibility of use to balance profit and benefits, and the agriculture sector, being a low-profit industry, is hard to capture. Table 2 critically highlights the hurdles towards utilization of nano-enabled solutions in agriculture, including biocompatibility with plants, delivery methods, and regulatory concerns, with reference to recent scientific findings.

6. Future outlooks and recommendations

The enthralling potential of nanotechnology towards technological revolution cannot be overlooked. However, there are serious concerns on the use of nanotechnology for agrotechnology revolution which should be considered. Therefore, intensive efforts are needed to identify the knowledge gaps and bring expected improvements to the futuristic technologies. In this regard, here we have some careful recommendations.

- Engineered nanoparticles provide a stronger control over modifications to obtain desired characteristics as per the targeted application. The engineering of nanomaterials in terms of shape, structure, size, and surface properties results in attaining key functionalities such as increased strength, catalytic activity, improved thermal and electrical conductivity, and controlled release of active ingredients in a target specific manner. Therefore, the use of ENPs should be preferred and more studies should focus on engineering of new nanoparticles.
- A more realistic approach needs to be adopted by the scientific community to ensure trust and mitigate the risks involved over the field use of engineered nanomaterials in agriculture, as for now, most of the studies are limited to identification, synthesis, and few applications validated by lab-scale trials only.
- Dosage optimization is a key challenge towards circumventing the negative impact of engineered nanoparticles in agriculture, therefore concentration-based studies in the natural environmental conditions need to be conducted to validate the accurate and non-toxic dose of nanomaterials.
- The study area should be broadened to include transgenerational transfer of impacts within the target crop, and the trophic chain transfer resulting from the applications of engineered nanoparticles.

Coupling these with the dosage optimization would result in deriving effective regulatory policies.

- It is imperative to have a deeper knowledge of the physiochemical properties of soil receiving the nanomaterials as the incompatibility will result in an increased chance of risk to plant health, imbalanced microbiota, and enhanced toxicity to the environment. Therefore, efficient soil management practices would ensure a safe and sustainable application of nanoparticles in agriculture.
- Last and most important, the use of engineered nanoparticles derived from biological sources should be given due preference to appreciate green synthesis with minimal associated risks. Eco-friendly approaches of nanoparticle synthesis and engineering should be validated by in-depth research and should be tested in natural conditions to have a clear picture of their environmental impact over the involved players (soil, microbiome, human health etc.).

Conclusively, we suggest studying the role of ENMs as systems rather than as individual components to avoid the unwanted shift of burden from one environmental component to another and ensure a sustainable future in terms of productivity and environmental sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (32072472), Zhejiang Provincial Natural Science Foundation of China (LZ19C140002), Key Research and Development Program of Zhejiang Province, China (2019C02006, 2020C02006), National Key Research and Development Program of Ningbo (2022Z175), State Key Laboratory for Managing Biotic and Chemical Threats to the Quality and Safety of Agro-products (grant number 2010DS700124-ZZ2014; -KF202101; -KF202205).

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