CellPress

Trends in Chemistry

Review

Designing nanoparticles for sustainable agricultural applications

Beza Tuga,[1] Tana O'Keefe,[1,3] Chaoyi Deng,[2,3] Andrea T. Ligocki,[1] Jason C. White,[2] and Christy L. Haynes[1,*]

Progress toward achieving global food security continues to be hindered by several economic, geo-political, and environmental variables which has led the United Nations to place emphasis on achieving Zero Hunger by 2030. Thus, it is important to invest in novel, eco-friendly, and cost-effective solutions that will increase agricultural productivity. For this reason, nanoscale materials are increasingly being developed for use in agriculture with attention on controlling various properties such as size, shape, surface modifications, and transformations for improved impact in plants. With continued interdisciplinary and collaborative efforts among nanoparticle experts and plant scientists, the research area will evolve to identify the best nanoparticle properties for foliar application to plants.

Highlights

Rapid population growth, global conflict, and the COVID-19 pandemic are all contributing to the surge in global food insecurity.

Nanoparticles (NPs) show promise toward alleviating food insecurity as several NPs used in greenhouse and field studies are outperforming conventional agrochemicals.

NP characteristics determine their uptake and translocation into plants.

Literature precedent demonstrates that it is possible to tune critical NP properties such as size, surface charge, shape, surface modifications, and transformations to impact the NP's performance within the plant.

While studies done to date are promising, more systematic studies with the most promising NPs are needed to achieve the full potential benefit of NP-enabled agriculture.

Nanoscale materials to alleviate global food insecurity

Engineered **nanoparticles** (NPs; see Glossary) have drawn special attention for various medical, commercial, and now, agricultural applications due to their emergent chemical and physical properties that are distinct from their bulk counterparts [1]. These properties can lead to enhanced ion dissolution and **transformation** as the large surface areas facilitate foliar attachment, chemical tunability, and plant uptake and transport [2–4]. In recent years, the use of NPs in agriculture has grown significantly, where NPs are being developed as sensors for monitoring plant health and pathogen detection [5–8], carriers to deliver beneficial cargo [9–13], and disease-suppressing agents against various plant pathogens [14–19] with the overall goal of finding solutions to global **food insecurity** (Box 1) [20]. The synthetic flexibility during NP design and synthesis enables scientists to use fundamental chemistry to design NPs with a desired size, surface charge, shape, surface coating and roughness, and the ability to transform (Figure 1, Key figure) [21–23]. Depending on the NP type, plant, and the desired application (i.e., sensing, delivery, or pathogen control), certain NP design expectations can be set with the goal of improving their performance within the plant [5,24].

In this review, we have assessed the recent literature to present the most promising design parameters that improve NP uptake and translocation as well as any notable increases in agricultural yield measures. We have limited the scope to foliar applied metal, nonmetal, metal oxide, and metalloid-based NPs that are likely to be successful in agricultural applications. Metallic NPs, such as gold- and silver-based NPs, are extensively used due to their established and tunable synthesis methods that allow for control over size and surface functionality, high mass contrast during analysis, and plasmonic features that allow for effective *in planta* characterization with low background signal in plants [25,26]. Several metalloid and metal oxide NPs are similarly drawing attention for their tunable synthesis and because they appear to be outperforming conventional commercial products specifically in plant disease suppression [4,27]. Farmers are being encouraged to incorporate various micro- and secondary macronutrients to better protect crops against disease and improve crop production [16,27]. Using nanoscale forms of these

[1]Department of Chemistry, University of Minnesota, Minneapolis, MN 55455, USA
[2]The Connecticut Agricultural Experiment Station, New Haven, CT 06511, USA
[3]Co-authors.

*Correspondence: chaynes@umn.edu (C.L. Haynes).

 https://doi.org/10.1016/j.trechm.2023.07.004

Box 1. Global food insecurity: a grand challenge with no clear solution

Our global food crisis is a long-standing issue with no clear solution. Based on this long-term and large-scale challenge, the United Nations identified Zero Hunger as one of the 17 Sustainable Development Goals; this goal aims to end hunger, achieve food security, and promote sustainable agriculture by 2030[i]. However, our progress toward achieving this goal is being undermined by growing global conflict, climate change, and, more recently, the coronavirus disease 2019 (COVID-19) pandemic [22]. The pandemic has primarily led to disruptions to global and national food supply chains while also causing economic hardships that are indirectly affecting food security [20]. In 2021, 2.3 billion people experienced moderate to severe food insecurity [22], and this number will continue to increase along with the growing world population that is expected to reach 9.7 billion by 2050 [21]. Over the last 50 years, the rate of agricultural yield increase for most crops has been declining but importantly, global agricultural productivity needs to increase by around 50% to meet the demands of our growing population [2]. Thus, the scientific community at-large is faced with the task of identifying creative, cost-effective, and environmentally friendly solutions that will aid in achieving this Zero Hunger goal within the next 7 years or sooner. Herein, we outline why NPs could serve as one component of the solution to this grand challenge (Figure 1, Part I).

nutrients [zinc oxide (ZnO), cupric oxide (CuO), and silicon dioxide (SiO_2) NPs] has been key to their success due to the increased, and in some cases controlled, ion dissolution as well as improved uptake and translocation in various plant species as is highlighted throughout this review. Since the field of nano-enabled agriculture is relatively new, it is challenging to be comprehensive and draw clear conclusions in this topic as the literature continues to develop. However, considerations of NP design rules prior to implementing experimentation can be invaluable toward propelling the field forward.

Plant considerations for nanoparticle use in agriculture

Before designing NPs for agricultural applications, it is critical to understand the application scenario and system of interest. Agriculture is an exceptionally broad field, including animal-based production, annual and perennial plant agriculture, and aquaculture. The growth conditions and nutrient requirements can be orders of magnitude different depending on the specifics of the system and the mode of application. The use of inappropriate NPs, or perhaps use of appropriate NPs in inappropriate application regimens, could lead to low efficiency of use or even harm target and nontarget species. Importantly, this review will focus exclusively on plant-based agriculture and potential effective and sustainable strategies that can be designed according to the decision tree shown in Figure 1, Part II. Moreover, when designing NPs to interact with plants, it is important to recognize that these species have evolved strategies over tens of millions of years to minimize the impact of foreign materials and xenobiotic particles. As such, some subtlety and thoughtful design is warranted. Further, efforts should always be made to minimize dose and exposure, for both economic and health (human and environmental) reasons. Importantly, the design rules will always be a direct function of the exposure route, the intended target, and the desired material. Each exposure route presents unique barriers that must either be bypassed or perhaps taken advantage of, and how that advantage can be incorporated will depend on what is being delivered (Box 2) [28–34]. The final plant growth conditions will be important as well; indoor or greenhouse-based, urban agriculture is distinct from acres of field production. Ultimately, only after a systems-level understanding is achieved (or at least recognized), can the desired material be appropriately designed.

Nanoparticle size

One common design strategy for controlling NP uptake involves tuning NP size. There are two main uptake mechanisms following **foliar application** of NPs: cuticular and stomatal pathways, with size limits of <5 nm and 10–80 μm, respectively (Box 2) [31,35]. Thus, NP size can dictate both the uptake mechanism and the amount taken up before translocation within plants.

Metal nanoparticles

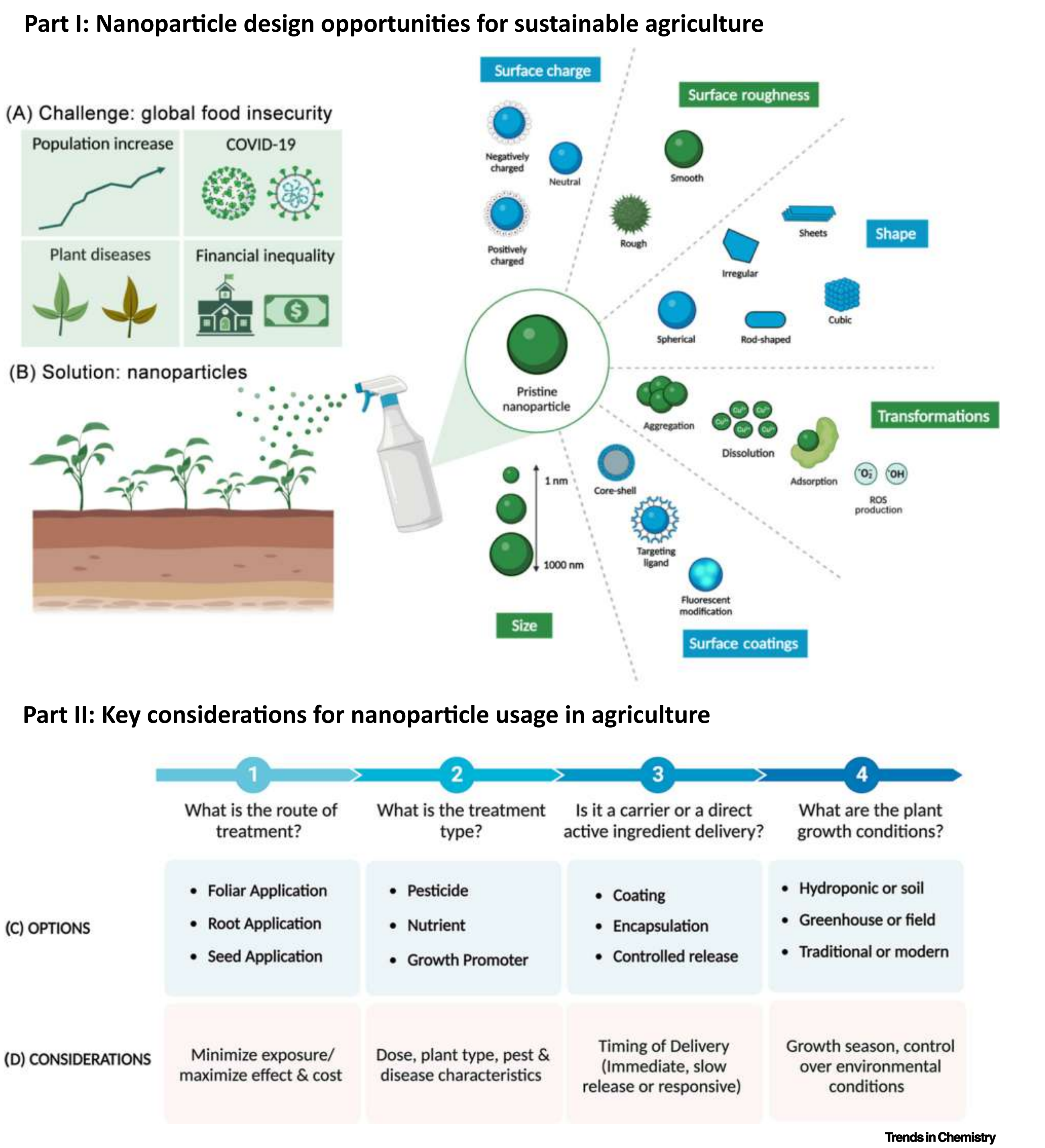
The uptake, translocation, and transformations of silver NPs (AgNPs) have been previously reviewed and suggest that leaves can take up AgNPs in the size range of 10–40 nm, although

Glossary

Biotransformation: changes to NPs in complex biological environments.
Dicot: flowering plants that contain two cotyledons (embryonic leaves).
Foliar application: spraying formulations directly onto plant leaves as opposed to the soil.
Food insecurity: lack of consistent access to enough food for every person in a household.
Food security: always having physical and economic access to enough food.
Monocot: flowering plants that contain one cotyledon.
Nanoparticle: particle with one dimension with a size of 1–100 nm and emergent chemical/physical properties.
Protein corona: biomolecules adhering to the NP surface.
Transformation: changes to NPs when introduced to different media.

Key figure

Nanoparticle design rules and considerations for plant application



(See figure legend at the bottom of the next page.)

precise size limitations for different plant species remain relatively unknown [36]. Su *et al.* [37] investigated AgNP foliar application in citrus trees. Six weeks after the application, the Ag recovered from the roots, branches, trunk, and leaves indicated uptake and translocation of the AgNPs with various coatings: polyvinylpyrrolidone (PVP), citrate (Ct), or gum Arabic. The AgNPs sizes ranged from 9 to 29 nm for the metal cores [37], agreeing with previous reports that were within the 10–40-nm range [36].

To further probe this effect, Zhang *et al.* [38] applied PVP- and Ct-coated AgNPs to spinach leaves and found that leaf penetration was more dependent on size than surface coating. The 40-nm-diameter AgNPs had a deeper penetration than the 100-nm-diameter AgNPs. In addition, the estimated percentage of internalized AgNPs, 0.2%–0.8%, was significantly smaller than that of the total Ag applied (9%–12%), suggesting transformation of the NPs inside the plant. This agrees with previous studies which indicate that smaller AgNPs undergo greater dissolution, allowing Ag^+ ions to translocate or complex with other ions or biomolecules within the plant [36,39–42].

More recent studies have suggested that gold NPs (AuNPs) larger than 40-nm diameter can enter through plant leaves. To explore AuNP transport, Avellan *et al.* [43] synthesized AuNPs, coated them with either Ct or PVP, that had diameters of 3, 10, and 50 nm, and foliarly applied them to wheat. For both coatings, 3-nm-diameter AuNPs had the best adhesion to the leaf surface after rinsing, followed by the 10-nm-diameter AuNPs, and then the 50-nm-diameter AuNPs. Hyperspectral microscopy images suggest all NP sizes could enter the plant leaves via cuticular uptake pathways which was impacted by the coating used. In addition, once inside the plant, similar transport to various plant compartments was observed for coated NPs of the same size. Another study led by Zhang *et al.* [44] revealed that when AuNPs of various sizes (5–20 nm) were infiltrated into model *Nicotiana benthamiana* plant leaves, smaller NPs were able to travel through plant tissue and associate with cells. Surprisingly, this study revealed that none of the spherical NPs were able to enter the intracellular plant space, noting that NP shape (see supplemental information online), rather than size, was integral for uptake. From these studies, it is evident that AgNP and AuNP size impacts the uptake within various plant models, with 50-nm or smaller NPs being ideal for plant uptake and transport.

Metalloid, metal oxide, and nonmetal NPs

Metal oxides, carbon dots, and metalloid NPs follow similar trends as those observed for AgNPs and AuNPs, with smaller NPs improving leaf adhesion and plant uptake. In one of the most systematic studies published to date, Hu *et al.* [45] synthesized hydrophilic carbon dots, cerium oxide (CeO_2) NPs, and silica (SiO_2) NPs with hydrodynamic diameters ranging from 1.7 to 18 nm, and applied them to cotton (a **dicot**) and maize (a **monocot**) leaves. NPs up to 18 nm penetrated cotton leaves via stomatal and cuticular pathways, whereas NPs up to 8 nm entered maize leaves through the stomata. This suggests a species-dependent and leaf anatomical difference for initial NP uptake and translocation. Furthermore, NPs up to 16 and 8 nm had higher association with the leaf guard cells for cotton and maize, respectively. This size-based difference in guard cell penetration is likely due to the cell wall size exclusion limit that is also plant species dependent. The authors also developed a NP–leaf interaction empirical model, based on

Figure 1. Part I: Nanoparticle design opportunities for sustainable agriculture. (A) Factors affecting global food insecurity: (1) Our world's population is expected to reach 9.7 billion by 2050 and the demand for food will increase by 70–100% [21]; (2) Disruptions to supply chains and economic shutdowns due to coronavirus disease 2019 (COVID-19) have adversely affected people's access to food [22]; (3) Plant diseases cause significant losses in crop production that lead to lower yields and species diversity [23]; (4) Loss of household income and the lack of available and affordable nutritious food are impacting access to food security [21]. (B) Nanoparticles as a solution to global food insecurity with infographic displaying the potential design strategies that can be used for plant application. Part II: Key considerations for nanoparticle usage in agriculture. (A) Lists potential options for nanoparticle treatment route, treatment type, delivery agent, and growth conditions that need to be addressed before starting a study. (B) Key considerations to keep in mind as the questions in part IIA are being reviewed. Figure created with BioRender.com.

Box 2. Anatomical barriers to nanoparticle entry into plant leaves

Foliar (or leaf) application is a common method of treating plants with NPs as it allows improved nutrient distribution and uptake compared with root application due to various avenues for NP entry [28]. Despite these serving as entry pathways, they may also limit the entry of NPs due to specific size or compositional exclusion limits which may serve as opportunities for careful NP design. The cuticle (Figure IB) is composed of an outer, more hydrophobic, layer that is rich in waxes called the cuticle proper and another layer referred to as the cuticular layer that is made up of cutin and polysaccharides [29]. The cuticle also contains small nanopores [30] that limit the entry of most NPs over 5 nm. A larger and likely more accessible NP entry pathway involves the stomatal openings (Figure IA) that are around 10–80 μm when open [31] and lack a cuticle covering [32]. The cuticle and stomata offer opportunities for affinity- or size-based design parameters; however, surface charge could also be influential, largely due to the chemical compositions of the plant cell wall. Figure IC shows a simplified plant cell schematic with the major biopolymers: pectin, cellulose, and hemicellulose highlighted. The free carboxylic acid groups present in pectin, which predominates the middle lamella, make the outer cell wall negatively charged [33] which would have higher affinity for positively charged NPs. Collectively, this knowledge of leaf anatomy is critical toward informing the design of several NPs.

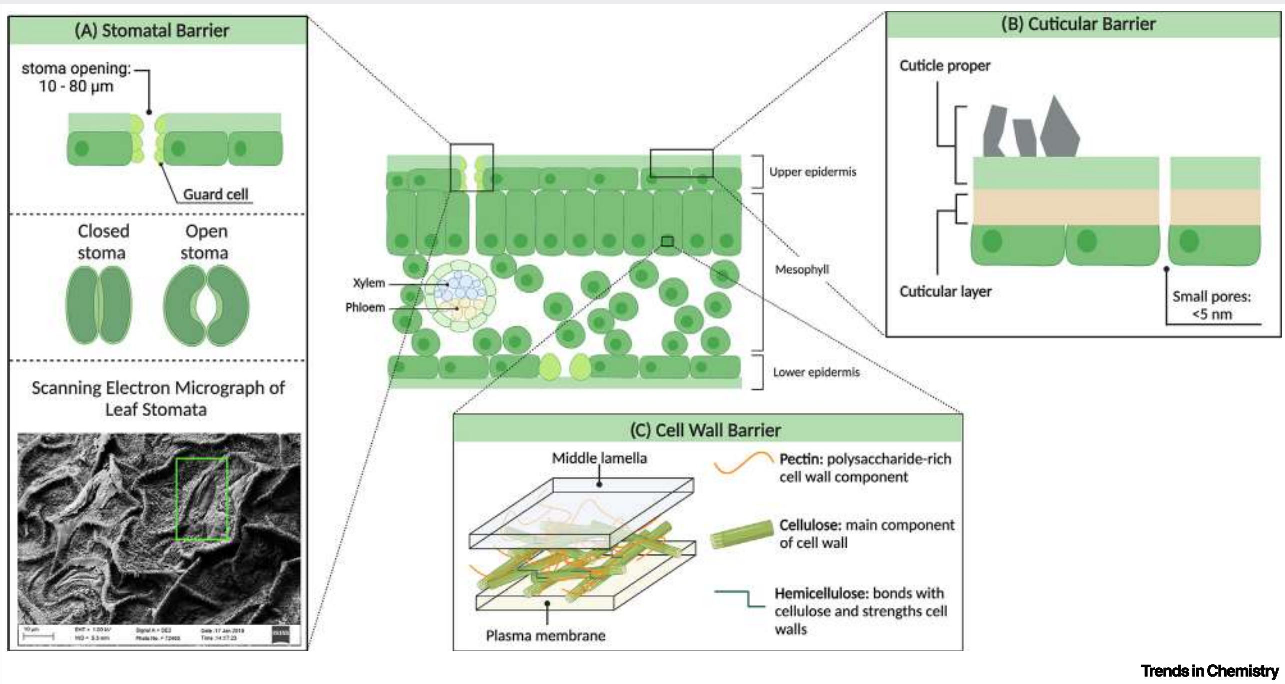


Figure I. **Transverse cross-section of plant leaf anatomy.** Figure highlights three major barriers to NP entry through (A) stomata, (B) cuticle, and (C) cell wall [29–31,33,34]. Figure created with BioRender.com.

hydrodynamic size and zeta potential, that predicts a 20- and 11-nm hydrodynamic diameter size limit for efficient NP delivery into cotton and maize guard cells, respectively [45]. However, other factors such as concentration, surface chemistry, and hydrophobicity would impact model outcomes; thus, there is a need for more systematic analyses of NP and leaf interactions to better model and predict the role of size in NP uptake.

Several related studies also provide evidence for NPs outperforming their bulk counterparts upon plant application. A study performed by Zhu *et al.* [46] found that large 200- and 500-nm ZnO bulk particles were more easily removed from wheat leaves with washing than their 40-nm counterparts. In addition, the 40-nm ZnO NPs were taken up through the stomatal pathway for leaf entry, excluding the larger particles. Once inside the leaves, the 40-nm ZnO NPs were also able to cross the cell wall into the cytoplasm, demonstrating the small size needed to readily cross the cell wall [46]. In a similar study, Zhang *et al.* [47] compared 20-nm ZnO NPs with zinc sulfate ($ZnSO_4$), an ionic control. The concentration of Zn within the NP-treated wheat grain was increased significantly and to a greater extent than $ZnSO_4$-treated plants. Higher uptake efficiency is likely due to the small NP size increasing adhesion on the leaf surface and slow dissolution of the ZnO NPs that provide a sustained Zn^{2+} pool as a nutrient for plant growth. Similar trends were observed when comparing 8-nm CeO_2 NPs with a 5-μm cerium acetate crystallites [48]. Lastly, El-Shetehy *et al.* [49] investigated SiO_2 NPs with a size range of 50–70 nm that entered the leaf through the stomata and were able to distribute within the large extracellular air spaces of the mesophyll. Successful uptake induced bacterial pathogen resistance in *Arabidopsis* plants by activating the plant's natural defense response [49]. While several mechanisms remain unknown for NP uptake and for improving plant health and yield, smaller NPs (often <50 nm) have beneficial impacts on several plant species.

NPs have relatively large surface areas that impact their leaf adhesion, uptake, translocation, and transformation within the plant. NP sizes in the range of 1–40 nm are ideal for foliar application; however, some studies do indicate that larger NPs (~50–70 nm) may still enter plant leaves through the stomata. Still, more systematic studies are needed for modeling and predicting NP uptake and translocation based on a NP's chemical and physical properties to allow for optimal design of NPs for various plant species. NP shape [19,50–57] and surface charge [33,45,46,58,59] are also design factors to consider because they can impact NP adhesion, uptake, translocation, and dissolution when applied to plants. Overall, these two factors appear to have a smaller impact than size; detailed analysis can be found in the supplemental information online.

Nanoparticle surface modifications

NP surface modifications may be incorporated to introduce new chemical or physical properties for a desired purpose. As the NP surface is the first point of contact with plant leaves, surface coatings have the potential to drive the impact and performance of NP in the context of transport and overall impact on plant yield. This section will analyze recent literature trends on the intentional surface coatings of metal, metal oxide, metalloids, and nonmetallic NPs with continued analysis presented in the supplemental information online [60–64,75].

Metal nanoparticles

As discussed above, PVP, an amphiphilic coating, and Ct, a hydrophilic coating, have been commonly used to modify Au and AgNPs to evaluate their uptake, translocation, and biodistribution in plants as a function of surface hydrophobicity. For example, when Avellan *et al.* [43] applied PVP- and Ct-coated AuNPs to wheat leaves, the hydrophobic moieties present in PVP allowed for better adhesion and improved interaction with the hydrophobic cuticle, making uptake more likely because the amphiphilic PVP-coated AuNPs are able to diffuse within the cuticle. By contrast, the Ct-coated AuNPs were easily rinsed off the leaf surface; yet, even with the limited contact time, some uptake occurred via stomatal openings. Interestingly, the performance of PVP- and Ct-coated NPs is reversed in the context of translocation, where the PVP-coated NPs were trapped in the mesophyll while the Ct-coated NPs had better translocation which improved overall plant health [43]. This more efficient delivery of Ct-coated NPs was also seen in a study that used AgNPs in the distinct plant system of citrus trees. Foliarly applied NPs allowed for uptake and translocation to various parts of the tree such as leaves (other than dosed leaves), branch/trunk, and roots based on the coating type. In terms of transport, the Ct coating allowed for more delivery to the tree branch/trunk than the PVP coating [37].

The success of Ct coatings for internal transport seems promising; however, a similar study by Spielman-Sun *et al.* [66] found that the Ct-AuNPs applied to broad bean leaves were randomly distributed around the leaf surface rather than achieving stomatal association as reported by Avellan *et al.* [43]. Both studies used the same design and synthesis strategy but show contrary results, which could be due to differences in the plant models used. In addition to the Ct-coated

NPs, Spielman-Sun *et al.* [66] also employed NPs coated with an anti-pectic polysaccharide antibody (LM6-M), which has specific affinity to, and can thus target, the stomata of broad bean leaves. This work reports the successful design of NPs with specific targeting moieties that were able to strongly adhere to the stomata [66]. Herein, we can infer that a targeted delivery approach, rather than surface hydrophobicity, may be more effective; however, follow-up translocation studies of LM6-M-coated NPs would further test this claim.

The complex biological environments within plants make it difficult to extract definitive reasons for translocation differences for Ct versus PVP coatings. Hence, identifying potential biomolecules that could interact with NPs and their respective coatings can enable a better understanding of NP transport. Like the studies above, PVP- and Ct-coated AgNPs were used in a study that used surface-enhanced Raman spectroscopy mapping to identify the amino acid cysteine as a significant biomolecule that interacts with AgNPs in spinach leaves [38]. The Ct coating showed a rapid interaction with cysteine while the PVP coating had a delayed interaction due to the bulkier nature of PVP preventing access to the Ag surface which caused it to mask the NP surface from cysteine. Future studies need to focus on elucidating the unique role of the biomolecular **corona** in plant uptake and translocation.

Metalloid and metal oxides nanoparticles

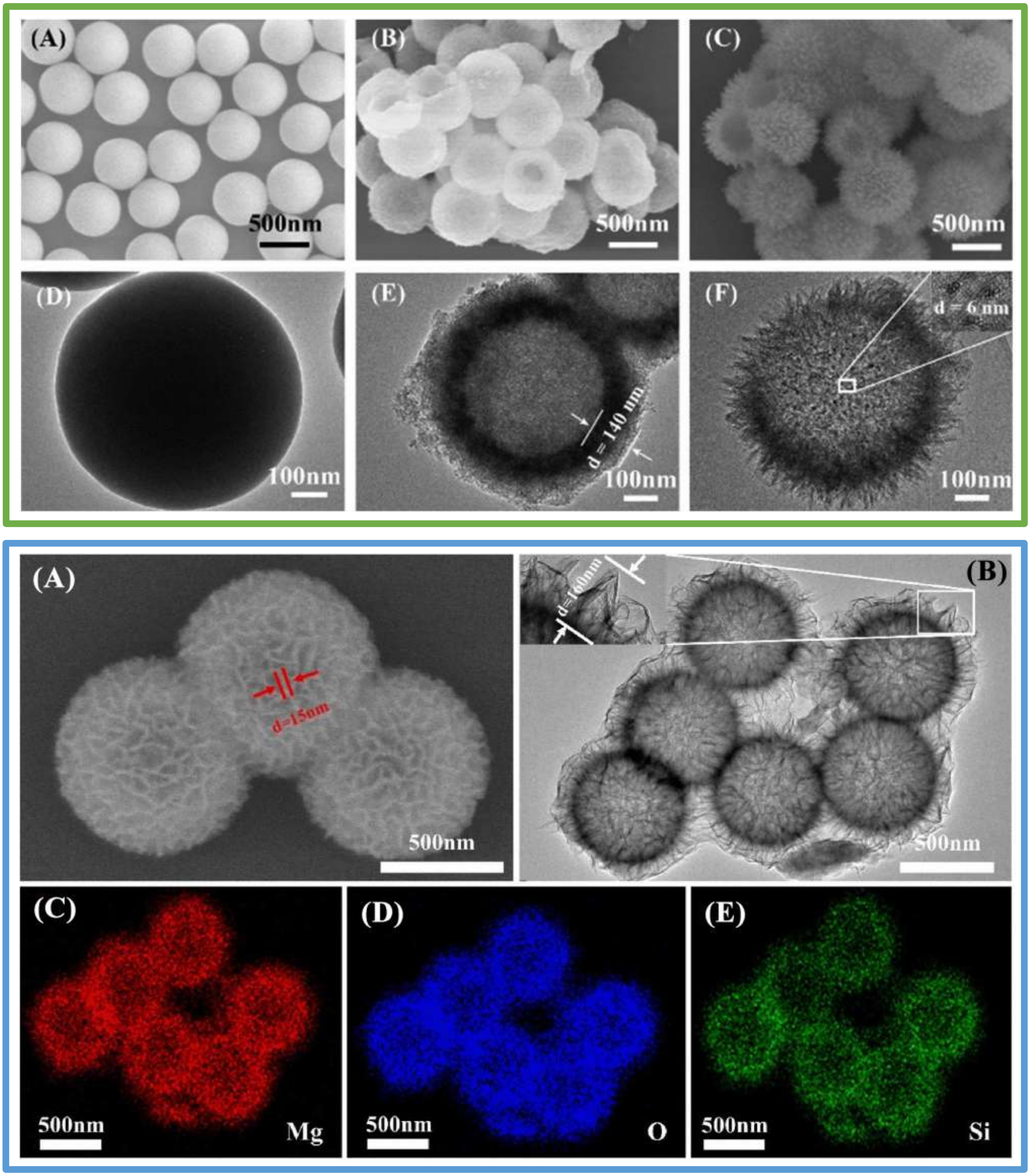
As the usage of metalloid- and metal oxide-based NPs increases, new application-driven surface modifications of NPs have emerged with a focus on tailoring NP uptake and localization as well as controlled release of target ions and other beneficial cargo for disease suppression and improved plant health.

For instance, Buchman *et al.* [18] coated mesoporous silica NPs with chitosan to aid in suppressing *Fusarium* wilt in watermelon through the dual delivery of beneficial silicic acid and chitosan. Chitosan-coated mesoporous silica NPs resulted in a 70% increase in watermelon yield in healthy plants which is an exciting outcome toward increasing global food supply. The well-developed and versatile synthesis methods for SiO_2 NPs allowed them to also serve as an NP coating in two similar studies that used SiO_2 NPs to encapsulate the pesticide azoxystrobin [67] and ZnO NPs [68]. Both studies showed that the presence of a silica coating allowed for a slow and continuous release of azoxystrobin and Zn^{2+} ions that were distributed within the stem > leaves > roots of tomato plants in each study. More interestingly, both studies characterized the uptake and translocation of nanoscale forms of SiO_2 and ZnO, and both NPs were present in stems, roots, and other leaves. In both cases, the silica coating was regarded as the source of success where Gao *et al.* [68] concluded preferential uptake for SiO_2-coated NPs (as the uncoated nanoscale ZnO NPs remained in the leaf).

Nanoparticle surface roughness

Strength and number density of NP adhering onto leaf surfaces can greatly influence leaf entry by NPs and the overall impact NPs may have on plants. While not widely studied, tuning the NPs' surface roughness has been investigated to improve leaf adhesion.

Li *et al.* [69] investigated sea urchin-like micro-nanostructured hollow silica spheres (SUH–Si) that had a 500-nm-thick uniform shell that was covered with a large number of silica urchin-like nanotubes (Figure 2C,F, top panel), increasing their surface roughness [69]. Compared with traditional foliar nitrogen fertilizers, the nitrogen fertilizer-loaded SUH–Si increased the adhesion on peanut and maize leaves by 5.9 and 2.2 times, respectively. This increased adhesion allowed for a more efficient delivery of the nitrogen fertilizer and promoted the maize plant growth and development [69]. The same group also designed a pompon-like magnesium foliar fertilizer (Figure 2B, bottom panel) that consisted of thin fold-like curled nanosheets on a hollow silica structure to increase leaf adhesion [70]. The pompon-like structure resulted in a sustained release of magnesium, and the foliar adhesion efficiency



Trends in Chemistry

Figure 2. Tuning surface roughness on core–shell nanoparticle systems. Top panel: scanning electron microscopy (SEM) images of (A) solid silica spheres, (B) hollow silica spheres, and (C) sea urchin-like micro-nanostructured hollow silica spheres. Transmission electron microscopy (TEM) images of (D) solid silica spheres, (E) hollow silica

(Figure legend continued at the bottom of the next page.)

on tomato leaves was improved by 10.4 times when compared with traditional magnesium foliar fertilizers [70]. Both studies indicate that increasing surface roughness positively impacts leaf adhesion and can result in more efficient delivery of common nitrogen- and magnesium-based fertilizers.

Uptake, translocation, and biodistribution are dependent on NP properties

NPs encounter a complex biotic and redox-sensitive environment within plants. The literature has shown that the uptake, translocation, and distribution of NPs in plant tissues are highly related to the NP properties discussed above. In addition, exposure time [60,71,72], aging and/or transformation processes of NPs [73,74], and plant species [65,75] all affect uptake processes.

When designing NPs, the role of exposure time to plants is an important consideration. Questions such as how fast the NPs should dissolve or release their ions and what is the optimum interaction time between NPs and the plant after the application are important factors that control NP usage efficiency. Wang *et al.* [60,61] reported that the uptake and translocation of sulfur NPs were highly time dependent, highlighting a time-sensitive window of physiological opportunity where these nanoscale crop protection strategies were successful. Importantly, surface functionalization of the material could be used to optimize activity as that impacts dwell time on and in plants. The effect of NP residence time or aging must also be considered when designing NPs. For example, rutile titanium dioxide NPs ($nTiO_2$) were weathered in field soil for 4 months prior to planting carrots for cultivation to full maturity [74]. The aging of $nTiO_2$ was highly dependent on the initial NP chemical properties, especially the surface charge, and the resulting differences in transformation processes can have overt impacts on biota. Specifically, the increases in taproot biomass, leaf fresh biomass, plant height, and nutrient element accumulation in the roots and leaves highlight the age-dependent loss of phytotoxicity as a function of $nTiO_2$ surface properties [62,74].

After accumulation in plant tissues, NPs encounter a complex chemical environment that may vary greatly in terms of pH, moisture, metabolite contents, and endophytic microbiome activity. For example, the accumulation of Cu content after nanoscale CuO exposure in Rosie bok choy was correlated with its higher anthocyanin than Green bok choy. Similarly, more Cu was translocated to the grain of wild rice than cultivated rice after nCuO exposure [64]. If the mechanisms behind these plant-specific differences could be understood, nanomaterials could be specifically synthesized to take advantage of the differences.

Biotransformation is dependent on NP properties

The **biotransformation** of NPs after plant uptake is largely dependent on the chemical composition of the NPs. With high surface-area-to-volume ratios, NPs such as nanoscale Ag, ZnO, CuO, and CeO_2 are thermodynamically unstable, as the Gibbs energies of synthesis reactions are often positive [76]. Therefore, these materials may undergo biologically driven dynamic transformations including aggregation, dissolution, adsorption, recrystallization, and redox reactions; these processes will be critical to controlling NP fate, distribution, and impact.

For example, the partial oxidation of AgNPs in the root tissues of ryegrass was attributed to two possible pathways: direct uptake by roots followed by oxidative transformation in root tissues or dissolution outside the root surface followed by the uptake of ionic species by roots [77]. With hydroponic ZnO NP exposure, Lv *et al.* [78] found that the majority of Zn accumulated in maize roots and shoots was in forms such as $ZnPO_4$, primarily due to the enhanced dissolution of ZnO NPs in the rhizosphere

spheres, and (F) sea urchin-like micro-nanostructured hollow silica spheres. Adapted, with permission, from [67] Copyright 2020 Royal Society of Chemistry. Bottom panel: (A) SEM and (B) TEM images of pompon-like magnesium foliar fertilizer and elemental maps of (C) magnesium, (D) oxygen and (E) silicon. Adapted, with permission, from [68] Copyright 2023 Royal Society of Chemistry.

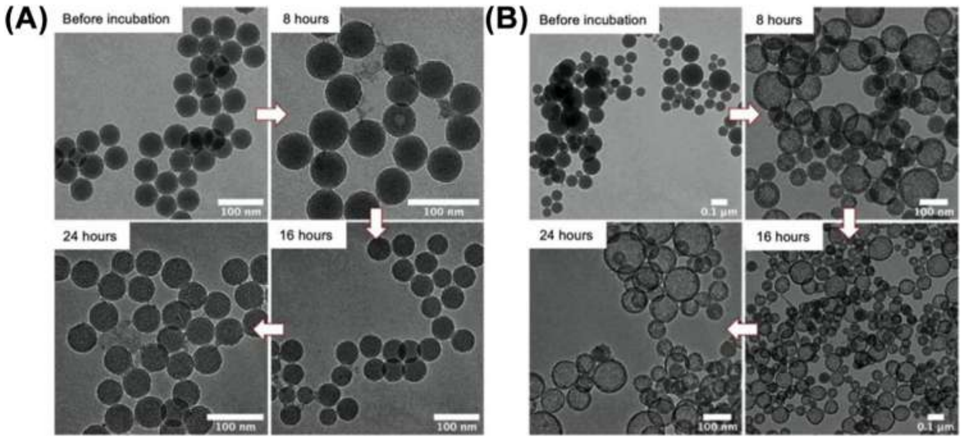


Figure 3. Time-based nanoparticle transformation micrographs. (A) Slow dissolving silica nanoparticles incubating in water over 24 h. (B) Fast dissolving silica nanoparticles incubating in water over 24 h with hollow structures formed in the first 8 h. Adapted, with permission, from [17]. Copyright 2021 American Chemical Society.

and plant uptake and translocation in the ionic form [78]. It has been reported that for ZnO NPs, the uptake, transport, and accumulation of Zn are primarily in the form of dissolved Zn^{2+} from the NPs. Consequently, surface modification could be employed to minimize rapid dissolution of ZnO, as well as to potentially control the rate of uptake and translocation. Interestingly, the *in planta* reduction of Cu(II) to Cu(I) has been reported in soil-cultivated rice and maize. Peng *et al.* [79] found that CuO NPs were transported from rice roots to shoots and that dissolved Cu(II) was mainly combined with cysteine, Ct, and phosphate ligands, but importantly, a fraction of the Cu(II) was reduced to Cu_2O.

Conversely, Au and SiO_2 NPs are present largely in their pristine form within plants [80]. However, Kang *et al.* [17,18,81] used synthesis conditions to control the SiO_2 NP dissolution (Figure 3); greater dissolution correlated with enhanced activity against *Fusarium* wilt in watermelon. This correlated with higher Si concentrations in the roots of plants that had been treated with faster dissolving NPs, indicating more effective silicic acid delivery. These findings suggest that NPs can be intentionally designed to control and take advantage of subsequent *in planta* transformation processes.

Concluding remarks and future perspectives

The motivation for this review is clear: our society continues to suffer from lack of global **food security**, and we need to invest in long-term and sustainable solutions to mitigate this impact. Innovations such as nano-enabled agriculture is providing us with an opportunity to overcome food insecurity. As with biomedical applications, NPs in agriculture require careful attention to NP properties that will determine their impact. Some properties include size, shape, surface modifications, and transformations of example metal, nonmetal, metal-oxide, and metalloid-based NPs that are applied to plant leaves, many of which are outlined in Table S1 in the supplemental information online.

This assessment of the current field of research reveals that it is difficult to identify optimal NP characteristics, but we can draw some conclusions that may guide future research. In terms of NP size and surface charge, the studies presented here show that smaller NPs (generally <50 nm) and positive surface charge seem to improve NP uptake into leaves. Perhaps surprisingly, novel analytical tools have revealed that NPs larger than 50 nm can travel throughout the plant vasculature. By contrast, studies that systematically evaluate the role of NP shape are lacking, but changing morphologies seem to improve disease and stress tolerance in some plants with no clear understanding (yet) of the underlying mechanism. Surface coatings add another layer of complexity as hydrophobic coatings may improve leaf adhesion and thus uptake, but once inside the plant, the impact of NP hydrophobicity on translocation is nuanced due to the complex biological environment present within plants. When incorporating coatings, it is important to include the coatings as part of the control treatments for greenhouse and field studies to properly elucidate any individual impact of the NP and/or coating. Lastly, NP transformations are generally considered a postsynthesis characteristic, yet the design properties mentioned throughout this review can facilitate a desired transformation. Future researchers should consider NP residence time within the plant when considering intentional control over transformations.

Despite the wide array of NPs available to us, it is important to account for the difficulty of synthesizing some novel NP systems with controlled properties as well as the need for efficient characterization methods to understand the system before plant application. In addition, several studies highlighted in Table S1 in the supplemental information online show commercial NPs that often lack extensive material characterization which eventually leads to no clear method of determining which property had the most valuable impact. Once inside the plant, there are several complex questions (see Outstanding questions) related to plant biology, growth, and plant species variation that need to be accounted for, and unfortunately, is the part of this challenge we do not currently have much control over. Lastly, for future commercialization, the cost, scalability, and acceptance of nanotechnology within the public needs to be taken into careful consideration. Toward these efforts, life cycle assessments of NPs, with a focus on the aforementioned material parameters, can help us better identify the datapoints needed to conduct a complete analysis of NPs in agriculture and thereby inform insights toward the sustainable implementations of these systems. Figure 4 shows some steps that need to be considered, which range from data

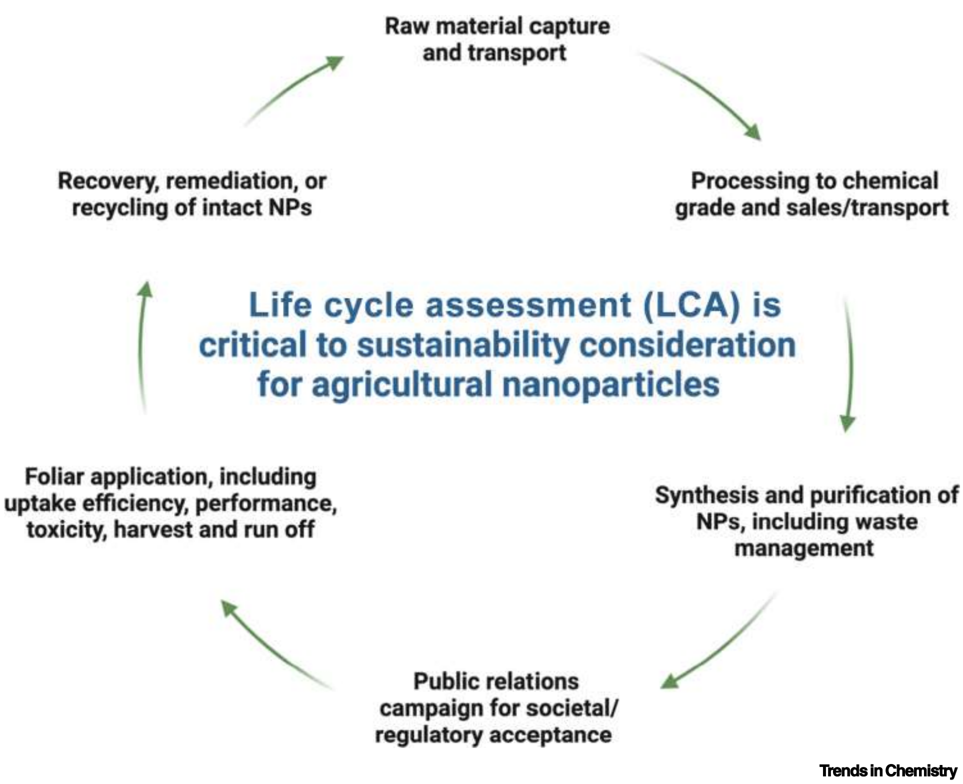


Figure 4. The life cycle assessment framework for nano-enabled agriculture. Highlighting key steps to consider for assessing the sustainability of nanoparticle (NP) application in agriculture. Figure created with BioRender.com.

Outstanding questions

How does the complex biological environment within plants affect the translocation of NPs within plants?

Can we develop more complex model experimental and computational systems, such as more complex model cell walls, that can help us understand the NP's mechanisms of action in plants?

Can we synthesize a library of NPs with various design properties that can serve to build robust computational models that will better delineate NP uptake and translocation within various plant species?

Is it possible to design NPs with coatings that will intentionally form protein coronas that will eventually improve transport throughout the plant?

Can we develop new or expand on current characterization methods to evaluate dynamic NP transformations so that we can have a 'live' view of NPs within the plant?

Can we generalize 'rules' for NP–plant interactions based on plant physiology to predict NP performance across plant species?

Can economically viable NP syntheses be scaled up for practical application?

How do we effectively communicate the benefits of NPs to the general public, industry, and political officials so we can eventually use these materials commercially?

collected by scientists at the bench to social scientists interfacing with the public that would consume the agricultural products. In conclusion, we hope this work emphasizes the need for more cohesive and systematic studies and thoughtful collaboration among researchers focused on NP preparation and the plant sciences.

Acknowledgments

This work is supported by the National Science Foundation under grant number CHE2001611, the NSF Center for Sustainable Nanotechnology (CSN). The CSN is part of the Centers for Chemical Innovation Program. B.S.T. acknowledges support from the University of Minnesota Graduate School's Interdisciplinary Doctoral Fellowship.

Declaration of interests

No interests are declared.

Supplemental information

Supplemental information associated with this article can be found online at https://doi.org/10.1016/j.trechm.2023.07.004.

Resources

[i]www.un.org/sustainabledevelopment/hunger/

References

1. Baig, N. *et al.* (2021) Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges. *Mater. Adv.* 2, 1821–1871
2. Kah, M. *et al.* (2019) Nano-enabled strategies to enhance crop nutrition and protection. *Nat. Nanotechnol.* 14, 532–540
3. Rodrigues, S.M. *et al.* (2017) Nanotechnology for sustainable food production: promising opportunities and scientific challenges. *Environ. Sci. Nano* 4, 767–781
4. Wang, D. *et al.* (2022) Nano-enabled pesticides for sustainable agriculture and global food security. *Nat. Nanotechnol.* 17, 347–360
5. Giraldo, J.P. *et al.* (2019) Nanobiotechnology approaches for engineering smart plant sensors. *Nat. Nanotechnol.* 14, 541–553
6. Ibrahim, H. *et al.* (2022) Wearable plant sensor for *in situ* monitoring of volatile organic compound emissions from crops. *ACS Sensors* 7, 2293–2302
7. Voke, E. *et al.* (2021) *In planta* nanosensors: understanding biocorona formation for functional design. *ACS Sensors* 6, 2802–2814
8. Wu, P. *et al.* (2022) A universal bacterial catcher Au–PMBA-nanocrab-based lateral flow immunoassay for rapid pathogens detection. *Anal. Chem.* 94, 4277–4285
9. Sigmon, L.R. *et al.* (2021) Biodegradable polymer nanocomposites provide effective delivery and reduce phosphorus loss during plant growth. *ACS Agri. Sci. Technol.* 1, 529–539
10. Santana, I. *et al.* (2022) Targeted carbon nanostructures for chemical and gene delivery to plant chloroplasts. *ACS Nano* 16, 12156–12173
11. Xu, T. *et al.* (2022) Enhancing agrichemical delivery and plant development with biopolymer-based stimuli responsive core–shell nanostructures. *ACS Nano* 16, 6034–6048
12. Gao, Y. *et al.* (2020) A bioresponsive system based on mesoporous organosilica nanoparticles for smart delivery of fungicide in response to pathogen presence. *ACS Sustain. Chem. Eng.* 8, 5716–5723
13. Ali, Z. *et al.* (2022) DNA–carbon nanotube binding mode determines the efficiency of carbon nanotube-mediated DNA delivery to intact plants. *ACS Appl. Nano Mater.* 5, 4663–4676
14. Elmer, W.H. and White, J.C. (2016) The use of metallic oxide nanoparticles to enhance growth of tomatoes and eggplants in disease infested soil or soilless medium. *Environ. Sci. Nano* 3, 1072–1079
15. Peréz, C.D.P. *et al.* (2020) Metalloid and metal oxide nanoparticles suppress sudden death syndrome of soybean. *J. Agric. Food Chem.* 68, 77–87
16. Servin, A. *et al.* (2015) A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. *J. Nanopart. Res.* 17, 92
17. Kang, H. *et al.* (2021) Silica nanoparticle dissolution rate controls the suppression of *Fusarium* wilt of watermelon (*Citrullus lanatus*). *Environ. Sci. Technol.* 55, 13513–13522
18. Buchman, J.T. *et al.* (2019) Chitosan-coated mesoporous silica nanoparticle treatment of *Citrullus lanatus* (watermelon): enhanced fungal disease suppression and modulated expression of stress-related genes. *ACS Sustain. Chem. Eng.* 7, 19649–19659
19. Borgatta, J. *et al.* (2018) Copper based nanomaterials suppress root fungal disease in watermelon (*Citrullus lanatus*): role of particle morphology, composition and dissolution behavior. *ACS Sustain. Chem. Eng.* 6, 14847–14856
20. Food and Agricultural Organization (FAO) (2021) The State of Food and Agriculture 2021. In *The State of Food and Agriculture (SOFA)*, FAO
21. Sadigov, R. (2022) Rapid growth of the world population and its socioeconomic results. *Sci. World J.* 2022, 1–8
22. UN Department of Economic and Social Affairs, *The Sustainable Development Goals Report 2022*, United Nations, 3–62
23. Ristaino, J.B. *et al.* (2021) The persistent threat of emerging plant disease pandemics to global food security. *Proc. Natl. Acad. Sci.* 118, e2022239118
24. Squire, H.J. *et al.* (2023) The emerging role of nanotechnology in plant genetic engineering. *Nat. Rev. Bioeng.* 1, 314–328
25. Kang, H. *et al.* (2019) Stabilization of silver and gold nanoparticles: preservation and improvement of plasmonic functionalities. *Chem. Rev.* 119, 664–699
26. Rycenga, M. *et al.* (2011) Controlling the synthesis and assembly of silver nanostructures for plasmonic applications. *Chem. Rev.* 111, 3669–3712
27. Elmer, W. and White, J.C. (2018) The future of nanotechnology in plant pathology. *Annu. Rev. Phytopathol.* 56, 111–133
28. Hong, J. *et al.* (2021) Foliar application of nanoparticles: mechanisms of absorption, transfer, and multiple impacts. *Environ. Sci. Nano* 8, 1196–1210
29. Yeats, T.H. and Rose, J.K.C. (2013) The formation and function of plant cuticles. *Plant Physiol.* 163, 5–20
30. Su, Y. *et al.* (2019) Delivery, uptake, fate, and transport of engineered nanoparticles in plants: a critical review and data analysis. *Environ. Sci. Nano* 6, 2311–2331
31. Jordan, G.J. *et al.* (2015) Environmental adaptation in stomatal size independent of the effects of genome size. *New Phytol.* 205, 608–617
32. Avellan, A. *et al.* (2021) Critical review: role of inorganic nanoparticle properties on their foliar uptake and *in planta* translocation. *Environ. Sci. Technol.* 55, 13417–13431
33. Delsart, C. (2016) Plant cell wall: description, role in transport, and effect of electroporation. In *Handbook of Electroporation*, pp. 1–22, Springer

34. Zhao, Y. *et al.* (2019) Advances in imaging plant cell walls. *Trends Plant Sci.* 24, 867–878
35. Eichert, T. and Goldbach, H.E. (2008) Equivalent pore radii of hydrophilic foliar uptake routes in stomatous and astomatous leaf surfaces – further evidence for a stomatal pathway. *Physiol. Plant.* 132, 491–502
36. Huang, D. *et al.* (2022) Uptake, translocation, and transformation of silver nanoparticles in plants. *Environ. Sci. Nano* 9, 12–39
37. Su, Y. *et al.* (2020) Delivery, fate, and mobility of silver nanoparticles in citrus trees. *ACS Nano* 14, 2966–2981
38. Zhang, Z. *et al.* (2021) *In situ* and real time investigation of foliarly applied silver nanoparticles on and in spinach leaves by surface enhanced Raman spectroscopic mapping. *Anal. Methods* 13, 2567–2574
39. Yang, Q. *et al.* (2020) Transformation and uptake of silver nanoparticles and silver ions in rice plant (*Oryza sativa* L.): The effect of iron plaque and dissolved iron. *Environ. Sci. Nano* 7, 599–609
40. Pradas Del Real, A.E. *et al.* (2017) Silver nanoparticles and wheat roots: a complex interplay. *Environ. Sci. Technol.* 51, 5774–5782
41. Li, W.Q. *et al.* (2020) Integration of subcellular partitioning and chemical forms to understand silver nanoparticles toxicity to lettuce (*Lactuca sativa* L.) under different exposure pathways. *Chemosphere* 258, 127349
42. Savassa, S.M. *et al.* (2021) Ag nanoparticles enhancing *Phaseolus vulgaris* seedling development: understanding nanoparticle migration and chemical transformation across the seed coat. *Environ. Sci. Nano* 8, 493–501
43. Avellan, A. *et al.* (2019) Nanoparticle size and coating chemistry control foliar uptake pathways, translocation, and leaf-to-rhizosphere transport in wheat. *ACS Nano* 13, 5291–5305
44. Zhang, H. *et al.* (2022) Nanoparticle cellular internalization is not required for RNA delivery to mature plant leaves. *Nat. Nanotechnol.* 17, 197–205
45. Hu, P. *et al.* (2020) Nanoparticle charge and size control foliar delivery efficiency to plant cells and organelles. *ACS Nano* 14, 7970–7986
46. Zhu, J. *et al.* (2021) Role of charge and size in the translocation and distribution of zinc oxide particles in wheat cells. *ACS Sustain. Chem. Eng.* 9, 11556–11564
47. Zhang, T. *et al.* (2018) Using synchrotron-based approaches to examine the foliar application of $ZnSO_4$ and ZnO nanoparticles for field-grown winter wheat. *J. Agric. Food Chem.* 66, 2572–2579
48. Adisa, I.O. *et al.* (2018) Role of cerium compounds in *Fusarium* wilt suppression and growth enhancement in tomato (*Solanum lycopersicum*). *J. Agric. Food Chem.* 66, 5959–5970
49. El-Shetehy, M. *et al.* (2020) Silica nanoparticles enhance disease resistance in *Arabidopsis* plants. *Nat. Nanotechnol.* 16, 344–353
50. Barker, B.T.P. and Gimingham, C.T. (1911) The fungicidal action of Bordeaux mixtures. *J. Agric. Sci.* 4, 76–94
51. Ma, C. *et al.* (2019) Time-dependent transcriptional response of tomato (*Solanum lycopersicum L.*) to Cu nanoparticle exposure upon infection with *Fusarium oxysporum f. sp. lycopersici*. *ACS Sustain. Chem. Eng.* 7, 10064–10074
52. Shen, Y. *et al.* (2020) Copper nanomaterial morphology and composition control foliar transfer through the cuticle and mediate resistance to root fungal disease in tomato (*Solanum lycopersicum*). *J. Agric. Food Chem.* 68, 11327–11338
53. Ma, C. *et al.* (2020) Advanced material modulation of nutritional and phytohormone status alleviates damage from soybean sudden death syndrome. *Nat. Nanotechnol.* 15, 1033–1042
54. Djanaguiraman, M. *et al.* (2018) Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. *ACS Omega* 3, 14406–14416
55. Chen, L. *et al.* (2022) CeO_2 nanoparticles improved cucumber salt tolerance is associated with its induced early stimulation on antioxidant system. *Chemosphere* 299, 134474
56. Liu, Y. *et al.* (2022) Foliar-applied cerium oxide nanomaterials improve maize yield under salinity stress: reactive oxygen species homeostasis and rhizobacteria regulation. *Environ. Pollut.* 299, 118900
57. Zhang, H. *et al.* (2019) Metabolomics reveals the "invisible" responses of spinach plants exposed to CeO_2 nanoparticles. *Environ. Sci. Technol.* 53, 6007–6017
58. Zhu, J. *et al.* (2020) Mechanism of zinc oxide nanoparticle entry into wheat seedling leaves. *Environ. Sci. Nano* 7, 3901–3913
59. Sun, H. *et al.* (2022) Surface charge affects foliar uptake, transport and physiological effects of functionalized graphene quantum dots in plants. *Sci. Total Environ.* 812, 151506
60. Wang, Y. *et al.* (2022) Therapeutic delivery of nanoscale sulfur to suppress disease in tomatoes: *in vitro* imaging and orthogonal mechanistic investigation. *ACS Nano* 16, 11204–11217
61. Wang, Y. *et al.* (2022) Surface coated sulfur nanoparticles suppress *Fusarium* disease in field grown tomato: increased yield and nutrient biofortification. *J. Agric. Food Chem.* 70, 14377–14385
62. Wang, Y. *et al.* (2021) Effects of different surface-coated $nTiO_2$ on full-grown carrot plants: impacts on root splitting, essential elements, and Ti uptake. *J. Hazard. Mater.* 402, 123768
63. Soliman, M. *et al.* (2022) Engineered zinc oxide-based nanotherapeutics boost systemic antibacterial efficacy against phloem-restricted diseases. *Environ. Sci. Nano* 9, 2869–2886
64. Deng, C. *et al.* (2021) Copper oxide (CuO) nanoparticles affect yield, nutritional quality, and auxin associated gene expression in weedy and cultivated rice (*Oryza sativa L.*) grains. *Sci. Total Environ.* 152260
65. Deng, C. *et al.* (2022) Soil and foliar exposure of soybean (*Glycine max*) to Cu: Nanoparticle coating-dependent plant responses. *NanoImpact* 26, 100406
66. Spielman-Sun, E. *et al.* (2020) Protein coating composition targets nanoparticles to leaf stomata and trichomes. *Nanoscale* 12, 3630–3636
67. Bueno, V. *et al.* (2021) Uptake and translocation of a silica nanocarrier and an encapsulated organic pesticide following foliar application in tomato plants. *Environ. Sci. Technol.* 56, 6722–6732
68. Gao, X. *et al.* (2021) Uptake and translocation of mesoporous SiO_2-coated ZnO nanoparticles to *Solanum lycopersicum* following foliar application. *Environ. Sci. Technol.* 55, 13551–13560
69. Li, W. *et al.* (2020) Improving the utilization rate of foliar nitrogen fertilizers by surface roughness engineering of silica spheres. *Environ. Sci. Nano* 7, 3526–3535
70. Li, W. *et al.* (2023) *In situ* construction of a magnesium foliar fertilizer with pH-controlled release and high adhesion capacity. *Environ. Sci. Nano* 10, 115–128
71. Rawat, S. *et al.* (2019) Differential physiological and biochemical impacts of nano vs micron Cu at two phenological growth stages in bell pepper (*Capsicum annuum*) plant. *NanoImpact* 14, 100161
72. Wang, Y. *et al.* (2021) Evaluation of the effects of nanomaterials on rice (*Oryza sativa* L.) responses: underlining the benefits of nanotechnology for agricultural applications. *ACS Agri. Sci. Technol.* 1, 44–54
73. Rawat, S. *et al.* (2018) Factors affecting fate and transport of engineered nanomaterials in terrestrial environments. *Curr. Opin. Environ. Sci Health* 6, 47–53
74. Wang, Y. *et al.* (2021) Soil-aged nano titanium dioxide effects on full-grown carrot: dose and surface-coating dependent improvements on growth and nutrient quality. *Sci. Total Environ.* 774, 145699
75. Tan, W. *et al.* (2018) Foliar exposure of $Cu(OH)_2$ nanopesticide to basil (*Ocimum basilicum*): variety-dependent copper translocation and biochemical responses. *J. Agric. Food Chem.* 66, 3358–3366
76. Cai, X. *et al.* (2020) Molecular mechanisms, characterization methods, and utilities of nanoparticle biotransformation in nanosafety assessments. *Small* 16, 1907663
77. Yin, L. *et al.* (2011) More than the ions: the effects of silver nanoparticles on *Lolium multiflorum*. *Environ. Sci. Technol.* 45, 2360–2367
78. Lv, J. *et al.* (2015) Accumulation, speciation and uptake pathway of ZnO nanoparticles in maize. *Environ. Sci. Nano* 2, 68–77
79. Peng, C. *et al.* (2015) Translocation and biotransformation of CuO nanoparticles in rice (*Oryza sativa L.*) plants. *Environ. Pollut.* 197, 99–107
80. Lv, J. *et al.* (2019) Uptake, translocation, and transformation of metal-based nanoparticles in plants: recent advances and methodological challenges. *Environ. Sci. Nano* 6, 41–59
81. Kang, H. *et al.* (2022) Effect of (3-aminopropyl)triethoxysilane on dissolution of silica nanoparticles synthesized via reverse micro emulsion. *Nanoscale* 14, 9021–9030