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Nanotechnology: Recent Progress in Agriculture and Effects on Physiology of Plants

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ABSTRACT

The naturally occurring and synthesised nanoparticles (NPs) display significant effects on the physiology of plants. This paper emphasised the current application of synthetic NPs in agriculture, several advantages and physiological responses during the growth of plants. Nano pore size of particles provides higher surface areas hence enhances the water holding capacity of the soil, efficacy delivery of fertilisers and pesticides (pest and diseases infestation) on crops. The application of NPs via soil or mist involves uptake by plant via roots or foliar cell wall and translocation to other organs through vascular system and plasmodesmata within the cells. The physicochemical properties of NPs have advantages including enabling the increase of soil water retention in mitigating the drought and/or salinity stresses in plants. Nanoparticles enhance the germination of seed and maintain plant growth by promoting the production of enzymes in scavenging oxygen radicals, phytohormone balancing, nutrient metabolisms and expression of amino acid biosynthetic genes and photosystem. Given the diverse physiological and molecular effects of NPs, precautionary steps prior to their application either as fertiliser or carrier should be considered to avoid toxicity and destructive effects on plants, animals, water body and the environment.

Keywords: Fertiliser; foliar; pesticides; phytohormone; nutrient; root.

INTRODUCTION

Nanoparticles (NPs) are one dimension of nanoscale materials that range from 1 to 100 nm. Generally, there are two types of NPs, which are naturally occurring and custom man-made or synthetic. The natural NPs are usually generated in uncontrolled conditions via natural processes such as ocean spray, forest fire, dust storms, volcanic ash and biological particles (such as bacteria and fungi). They are present in the soil as clay (8 to 28%), water body as colloid (0.4 to 7%) and in the atmosphere (0.1 to 1.5%) (Burman and Kumar, 2018). On the other hand, the synthetic NPs are mostly amorphous, various in sizes but still in nanometre-scale with highly reproducible physicochemical properties. These include carbon-based NPs or graphene, which are normally used in structural reinforcement; in ceramic mixed with inorganic solid of oxides. Carbonates and phosphates are commonly used as catalysts, photodegradation of dyes and for drug delivery. Metal and/or metal oxides that are chemically synthesised via electrochemical or photochemical methods are usually used as bioanalytical and imaging biomolecules, photocatalyst in semiconductors, electronic devices, photo-optics and water splitting. These are liquid-based with the spherical shape of 10 to 100 nm diameter stabilised by surfactant and emulsifiers. NPs are also commonly used in biomedical, drug carrier and delivery, and RNA release in cancer therapy (Khan et al., 2019; Cheng et al., 2021).

The term "nanotechnology" was first coined in 1981 by Professor Norio Taniguchi after the development of a scanning tunnelling microscope that enables us to see an individual atom (Bayda et al., 2020). Nanotechnology involves manipulating and controlling nanomaterials (NMs) in a useful way. Over the years, nanotechnology has been progressively utilised in numerous fields not limited to electronics, but the usage has expanded to biological sensors, water treatments, textiles, cosmetics, detergents and paints. It was reported that the estimated annual worldwide production of NMs is more than 10, 000 tones which are mostly contributed by metal or metal oxide-based NPs (Piccinno et al., 2012). Surprisingly, the $AgNO_3$ NPs alone were produced at approximately 500 tones/year (Syafiuddin et al., 2018). To date, NPs are also being used in the agriculture industry for many purposes such as crop production (plant protection, nano fertilisers and precision farming), improvement of soil health, water refinement and pollution remediation, diagnostic (nanosensors and diagnostic devices for livestock and fisheries) and plant breeding (DNA carrier in plant genetic transformation) (Pramanik et al., 2020). In plant biotechnology, the applications of nanotechnology especially NPs are expanding tremendously with the aims to improve crop productivity (Khot et al., 2012; Shang et al., 2019; Rastogi et al., 2017; 2019) and yield.

Therefore, this paper describes the physiological effects of NPs application in agricultural crop plants. Evidence showed that plant responses towards NPs are dependent on the type, size, morphology (nontoxic of aggregate) and physicochemical properties of NPs (Remedions et al., 2012). In various shapes, nanoparticles have a greater surface area-to-weight ratio. Hence, they display better unique chemical and physical properties that include easily and widely spread, significantly higher rate of absorptions through roots or leaves (Feizi et al., 2012; Amrullah et al., 2015; Shen, 2017) compared to their natural bulk size. NP technology is a promising field for the development of new products, the particle interacts unexpectedly with biological systems and is practically suitable for crop management (Shang et al., 2019; Rastogi et al., 2017; 2019). Nonetheless, eco-friendly and environmentally safe nanotechnology must be the key choice in crop management which also factorises conditions under unpredictable climate change (Usman et al., 2020). Among the NPs, silica oxide (SiO_2) has gained huge attention in agriculture. It was reported that the Si-nanoparticle have been used as nutrient carrier such as urea to promote plant growth and development as well as nanosensor for crop monitoring. Si-NPs have also been used to improve soil fertility and water retention capacity in mitigating the environmental stresses due to high salinity, drought and heavy metal pollutions (reviewed by Ng et al., 2021) as illustrated in Figure 1.

IMPROVEMENT AND MANAGEMENT OF SOIL FERTILITY

Soil fertility, crop productivity and yield are reliant on the fertiliser uptake and delivery. Evidence showed that the conventional fertiliser applications such as broadcasting and spraying cause losses of fertilisers through leaching, drifting, runoff water, evaporation, soil moisture-driven hydrolysis, and microbial and photolytic degradation. Pramanik et al. (2020) reported that the fertiliser losses were up to 70% of nitrogen, and 90% of phosphorus and potassium. Furthermore, excess usage of fertilisers and pesticides can cause environmental pollution, degradation of natural resources, the resistance of pests and pathogens toward pesticides, reduction of microflora and nitrogen fixation microbes, and pesticides bioaccumulation (Prashar and Shah, 2016; Sharma et al., 2019; Shrivastava et al., 2019). Therefore, optimal usage of chemical or synthetic fertilisers for crop growth with minimised environmental pollution are required. As a solution, the non-toxic nanomaterials or nanotechnology known as smart fertilisers could be supplied singularly or as a cocktail of multi-nutrients. Due to the ultra-small size, NPs provide large surface area, the usage of nanotechnology is viable to enhance the growth, yield and nutritional quality of crops. A nano fertiliser can deliver nutrients to specific target sites, improve efficiency of nutrient uptake and usage, and reduce environmental degradation (Mittal et al., 2020).

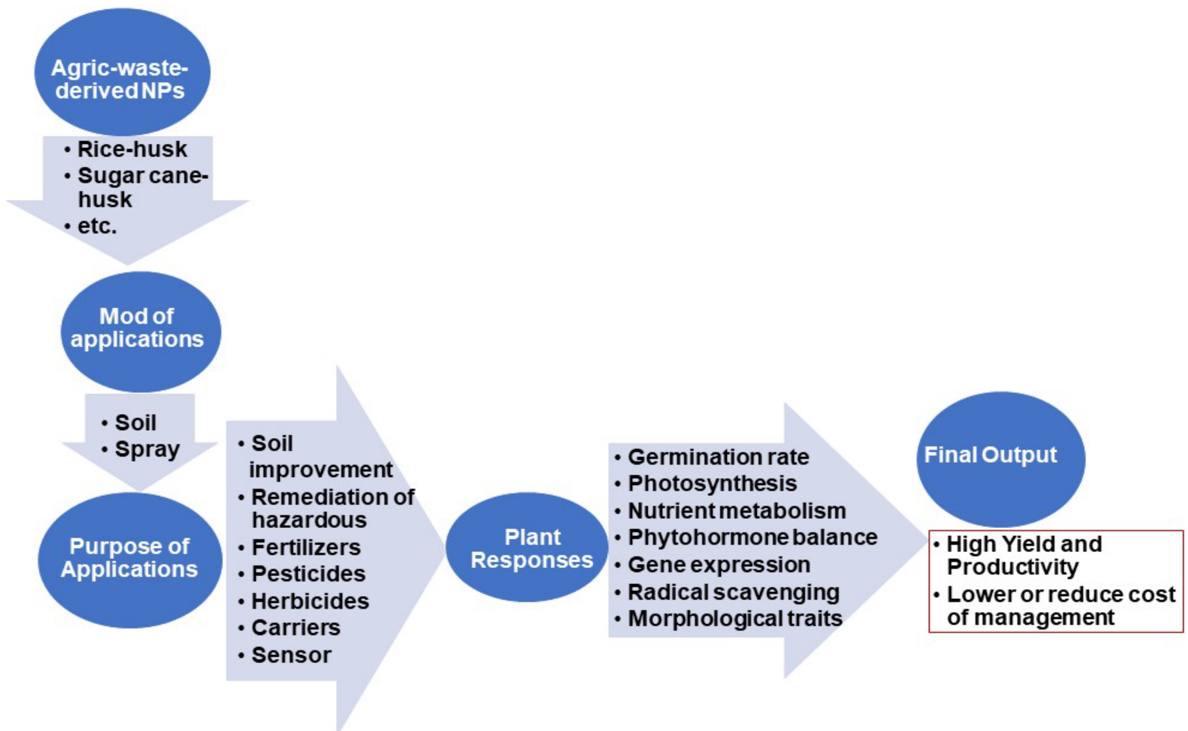

Figure 1. General overview of the application of non-toxic nanoparticles in agriculture (modified from Ng et al., 2021).

Other advantage of nanoparticle is that it can be encapsulated as nanofertiliser. In general, encapsulation could be made in three ways as stated by Rai et al. (2012), which are encapsulation in nano-porous materials, coated with a thin-film polymer or delivered as nanoemulsions. These formulations possess high solubility, timely and controlled release, stability, efficacy, improved distribution of attached compound to the targeted cell, and safe distribution and disposal. Solanki et al. (2015) mentioned that the NPs attached to nutrient are prepared by absorption, nanoparticulate polymeric shell encapsulation, ligand-mediated attachment, synthesis of nutrient-rich nanoparticle and polymeric nanoparticle entrapment. For instance, the mesoporous Si-NPs (150 nm) have been used as the vector for boron (B), urea and nitrogenous based fertilisers (Wanyika et al., 2012; Rajanna et al., 2015, Janmohammadi et al., 2016; Rastogi et al., 2019). Si-NPs can trap urea hence reducing urea release time by five-fold with 15.5% urea encumbered inside the mesoporous beneficially inhibiting urea discharge into the water source and soil (Wanyika et al., 2012). Additionally, mesoporous nanoparticles that are 2 to 10 nm in size could efficiently assist the delivery of fertiliser or active substances for both pesticides and herbicides. Nanocarriers increase the efficacy of pesticides, such as pyoluteorin and avermectin (Rouhani et al., 2012; Magda and Hussein, 2016). Si-NPs (0.01 g/m^2) have also been used as carriers of chlorpyrifos that exhibit 100% mortality of both insect species, the *Tribolium confusum Jacquelin* du Val and *Rhyzopertha dominica* F. (Satehi et al., 2018).

REMEDIATION OF ENVIRONMENTAL STRESSES AND HAZARDOUS

Rapid climate changes are uncontrolled phenomena that cause drought and flooding together with rising sea levels that threaten agriculture, especially in the coastal regions. Water retention and infiltration in the soil are important for soil health, crop growth and development. The application of Si-NPs could act as a component of nano-zeolite in enhancing capacity of water holding and release to facilitate both water intrusion and retention in the soil (Rastogi et al., 2019; Mahmoud et al., 2020). Foliar application of SiO_2-

NPs at 600 mg/L was reported to improve the photosynthetic rate, K^+ and K^+/N^+ to maintain the integrity of Cavendish banana planted under saline conditions. Additionally, both the formation of malonyl dialdehyde (MDH) as well as electrolyte leakage were also reduced (Mahmoud et al., 2020). Elsheery and co-workers (2020a, b) reported that foliar spray of Si-NP was reported to ameliorate the chilling effects on sugar cane by increasing the PS-II photochemical efficiency (*F*v/*F*m), maximum photo-oxidable PS-I (*P*m), photosynthesis gas exchange, chlorophyll and carotenoid content.

Si-NPs rich soil with amendments such as Si-fertilisers, Si-mineral, rice husk and/or biomasses of straw and other biochars were reported to reduce the arsenic (As) toxicity in paddy soils and build up in rice grains (Chen et al., 2018; Herath et al., 2020). Other heavy metal toxicity such as by cadmium (Cd) and lead (Pb) was also alleviated by the Si-NPs (Emamverdian et al., 2020; Khan et al., 2020). The use of 500 µM of SiO_2-NPs has increased the activity of the antioxidative enzymes (catalase, glutathione reductase, superoxide dismutase and phenylalanine ammonia-lyase) as well as the chlorophyll and carotenoid in the Pb-stressed bamboo, *Pleioblastus pygmaeus* (Emamverdian et al., 2020). Interestingly, SiO_2-NPs also protected the integrity of the bamboo plasma membrane by reducing the formation of hydrogen peroxide (H_2O_2), soluble protein and polyphenol oxidase activity. Foliar application of Si-NPs was reported to reduce cadmium (Cd) accumulation and inhibit Cd transportation in rice plants (*Oryza sativa* L cv. Xiangzaoxin-45) grown in Cd-contaminated land (Chen et al., 2018). The activity of antioxidants, oxidative enzymes and chlorophyll were also increased in rice (Wang et al., 2015) and wheat (*Triticum aestivum* L) in soil contaminated with Cd (Khan et al., 2020). Application of SiO_2-NP combined with Triton-X 100 on *Erigeron annuss* L was reported to enhance the degradation of phenanthrene, a toxic polycyclic aromatic hydrocarbon (PAH) by the plant (Zuo et al., 2020).

PRECISION FARMING

Smart farming and precision agricultural approaches deal with the sensing and data analysis process (data mining and visualisation), the decision-making process (decision-support systems, modelling and planning tools) and the action process such as online applications, monitoring robots and automation technologies (Zervopoulos et al., 2020). The advancement of nanotechnology-based concepts in precision farming allows incessant control of the farmland condition by monitoring the network of plant health and alerting the user and even providing various suggestive decisions. The process requires an operative blend of mechatronics and information and communication technology (ICT) for agriculture applications, known as 'agrinfortronics'. Future agriculture is highly dependent on the knowledge of price and consistent data about the crop production environment. Ambient intelligence is an emerging discipline that utilises artificial intelligence and sensors to anticipate individual needs and respond accordingly.

'Smart dust' is a tiny device with extensive application in science and technology. These few millimetre-sized devices consist of multiple small wireless microelectromechanical systems (MEMS) of 20 µm in size that are individually operated using a very small power supply. MEMS or motes are equipped with cameras, sensors and communication mechanisms (Bose, 2020). These are eventually connected to a wireless computer network to process the data acquired through radio-frequency identification (RFID) technology. These tiny devices are created using conventional silicon microfabrication techniques and can be suspended in a farm area similar to dust. Among various occupations of smart dust are collecting numerous data (acceleration, humidity, light, temperature, pressure, sound, vibrations and stresses), processing and storing of data, transmitted from one mote to another mote until they reach the transmission mode (wireless transfer to the cloud, a base and other MEMS) (Bose, 2020).

NANOMATERIAL UPTAKE

The uptake of artificial NPs by plants either apoplastic and/or symplastic before translocation to other plant vascular systems is influenced by the physical properties, which are the overall size, surface area and mechanical properties (Rastogi et al., 2017; 2019; Usman et al., 2020). In most plants, the size of NPs dictates symplastic transport. NPs that are lower than 5 nm are easily translocated through the pores of the cell wall, while those in the range of 8 to 20 nm move preferably between cell plasmodesmata, and particles that are larger than 50 nm are internalised via endocytosis (Behzadi et al., 2017). Chemical composition and coating on the NPs surface were reported to regulate the chemical stability such as redox state, covalent attachment and persistent binding to biomolecules (Abarca-Cabrera et al., 2021). The biological activity of NPs was also influenced by their formation whether in aggregation or individual. Previous studies showed that aggregated NPs exhibit lower toxicity compared to the individual forms once in plants, bacteria or fungi (Remedios et al., 2012; Ameen et al., 2021). Nonetheless, the magnitude of toxic NPs released to the environment that are being used in the agriculture industry remains a concern owing to their adverse effects on organisms (Garcia-Sanches et al., 2021). Due to their sizes being smaller than bacteria which are known can be transmitted across organs, these toxic NPs can be accumulated in plants through uptake, translocation and eventually stored in cells (Mohd Rased et al., 2019; Shamsudin et al., 2019). However, plant response towards NPs is dependent on physicochemical properties, application method, plant species, growth stages, water and nutrient availability.

SEED GERMINATION

A high seed germination rate is very important to the reproduction of seed-derived crops. A low germination rate increases the cost, time and energy of farmers. A previous study showed that ground application of SiO_2-NPs (50 nm) enhanced the germination rate of maize or corn up to 100% (Karunakaram et al., 2013) as well as increased the population of bacteria in the soil. Siddiqui and Al-Whaibi (2013) reported that 8 g/L of SiO_2-NPs improved seed germination, germination index, seed vigour index and seedling biomass of tomato (*Lycospercisum esculentum* Mill). Mesoporous SiO_2-NPs (20 nm) was also reported to increase seed germination of lupin and wheat (Sun et al., 2016). Another NP used to aid seed germination is titanium dioxide (TiO_2) nanoparticles (Khot et al., 2012).

PHYSIOLOGICAL RESPONSES FOR PLANT HEALTH AND PRODUCTIVITY

Nanoparticles may contribute to the positive and negative impacts on the physiology of plants. The toxic NPs cause toxicity and damage to the plant cell structure, while the positive impacts would promote plant health and productivity and yield (Table 1). Plant health is strongly connected with nutrient uptake and nitrogen metabolism. Studies have shown that the utilisation of NPs directly promotes growth of plant by increasing the morphological traits (Amrullah et al., 2015; Ahmad et al., 2020), physiological structures (Rangaraj et al., 2014; Khan, 2021), photosynthetic related proteins (Wang et al., 2020a, b), chlorophyll content (Sun et al., 2016) as well as permits the translocation of mineral nutrients (Chen et al., 2018). Foliar spray of micronutrients in other fruit crops also exhibited a similar response by increasing yield and fruit quality (Lalithya et al., 2014). Among nutrients, assimilation of nitrogen is a vital process that regulates plant growth and development. Pradhan et al. (2014) demonstrated that manganese nanoparticles (Mn-NPs) are involved in nitrate uptake, assimilation and metabolism in mung beans. Mn-NPs have partially impaired the activity of nitrate reductase, nitrate reduction, glutamate synthase (GS) and NADH-glutamate synthase (GOGAT) activities. The study also showed that Si-NPs easily enter plant cells and accumulate at different plant parts (Sun et al., 2016; Chen et al., 2018) stimulating variations in the metabolism and facilitated photosynthetic activity (Rastogi et al., 2019). A combination of oligochitosan with SiO_2-NP (10 to 30 nm) applied as foliar spray increases soybean yield (Phu et al., 2017). Indirect effects of NPs were associated with the increase in nutrient and microbial population of soil, and stress mitigation (Karunakaram et al., 2013; Rangaraj et al., 2014).

Table 1. Examples of the positive impact of nanoparticles on the physiology of plants

Nanoparticles	Physiological Response	Reference
CuO_2 and ZnO_2	Induced the root formation of *Stevia rebaudiana,* increased the phytochemicals, rebaudioside A and stevioside production.	Ahmad et al. (2020)
CeO_2 and CuO_2	Foliar application on cucumber has increased the fresh weight. Soil amended with Cu-NPs increased the nutrient and allicin content in the Chinese scallion (*Allium fistulosum*)	Wang et al. (2020a, b)
TiO_2	Soil amended with the NPs has increased the leaf biomass of tomato (142%) and fruit yield (102%). There were changes in the elements of Fe, B, P, Na and Mn in stem and leaves and less in fruits	Bakshi et al. (2019)
CeO_2	Foliar was more effective than soil application on bean (*Phaseolus vulgaris*), which increased the stomatal length, alteration of photosynthesis and electron transport chain	Salehi et al. (2018)
CuO_2	Soil amended with Cu-NPs showed increased seed number of green pea (*Pisum sativum*) to 163.5%	Rahman et al. (2020)

Phytohormones are plant growth regulators at various physiological stages such as cell division and elongation, metabolism, stress relief, germination of seed, flowering and senescence. A study has shown that the presence of NPs in vascular tissues have altered the phytohormone concentrations in the specific organs that leads to physiological and biochemical changes in plants. Application of ZnO-NPs was shown to affect the growth of cotton (*Gossy hirsutum* L) by increasing the biosynthesis of indole-acetic acid (IAA) and zeatin (Venkatachalam et al., 2017). Meanwhile, SiO_2-NPs affected the levels of abscisic acid (ABA) and CuO-NPs elevated the levels of IAA, ABA and GA. Pociecha et al. (2021) demonstrated that silver nanoparticles (AgNPs) and silver ions differently affected the phytohormone balance and yield in wheat.

SELF DEFENCE

In crop production, weed and pest management is vital and very costly. Both, natural and synthetic chemicals of pesticides have been employed in various agricultural practices to manage the pests, weeds and diseases in crop plants. It has been estimated that the pesticide application in agriculture will be increased up to 3.5 million tonnes annually (Sharma et al., 2019). To date, numerous types of nanoparticles have been applied in agriculture to enhance agrochemical efficiency as well as reducing the chemical quantity in managing the phytopathogens and weeds (Rastogi et al., 2019; Madany et al., 2020; Usman et al., 2020). The uniqueness of Si-NPs physicochemical properties is the advantage to be used as foliar spray for maximum absorption of pesticides-nanoparticle mixture. The pathogen infection is reduced through the formation of thin film coating on the leaf surface after spraying with nanoparticles. For instance, the application of potassium silicate nanoparticle has strengthened the activity of cuticle as a mechanical barrier against infiltrations of pathogen (Menzies et al., 1992). Kanto et al. (2004) reported that the soluble Si had changed the biochemical composition of the cuticle layer and inhibited germination of conidia, *Sphaerotheca aphanis.* Subsequently, it decreased the rate of pathogen infection and formation of disease (Buck et al., 2008).

Amorphous nano-silica itself has been demonstrated as a promising pesticide in controlling various insect pests in agriculture (Rouhani et al., 2012; Magda and Hussein, 2016; Satehi et al., 2018). The Si-NPs were physiosorbed by the pest cuticular lipids. Consequently, disrupting the defensive barrier and causing the death of pests by physical means. Furthermore, foliar application of Si-NPs did not modify either photosynthesis or respiration in some groups of plants, neither altered gene expression of insect trachea nor approved as a nano-biopesticide. The amorphous silica (non-crystalline silica) use as a nano-biopesticide is considered harmless for humans by the World Health Organization (WHO). In plants, the mesoporous SiO_2-NPs (~ 20 nm) will be taken up by the root through the apoplastic and symplastic pathways and translocated to the aerial plant parts through the xylem prior to be deposited in the cell walls (Sun et al., 2016). The deposition of NPs indicated the existence of an affinity with the cell wall components (Luyckx et al., 2017) that may perform as a physiological blockade against pathogen infection. Nevertheless, the NP interaction mechanisms at the molecular level of plant systems remains scant due to the action of nanoparticles on cellular structures (Jha and Pudake, 2018). Furthermore, evident showed that the NP effects are dependent on plant species, pH and surfactant concentration (Sun et al., 2014). Slomberg and Schoenfisch (2012) described that the larger size of Si-NPs (~ 200 nm) did not cause phytotoxicity in the root of *Arabidopsis thaliana*. Nonetheless, higher concentration of SiO_2-NPs through foliar application is toxic (Suriyaprabha et al., 2014). This may be attributed to the high pH of SiO_2-NPs and nutritional imbalance (Slomberg and Schoenfisch, 2012). Mesoporous nano-SiO_2 (20 to 150 nm) significantly inhibited the growth of early blight (*Alternaria solani*) on tomatoes (Derbalah et al., 2018). Debnath et al. (2010) reported that Si-NPs caused total mortality in rice weevil, *Sitophilus oryzae*. Moreover, the charges on the surface of hydrophobic molecule of Si-NPs (3 to 5 nm) effectively controlled a wide range of agricultural pests. NP thin film applied on seeds have reduced the fungal growth and also improved cereal germination rate (Ghormade et al., 2011). It was demonstrated that Si-NPs had poisonous effects on *Callosobruchus maculatus* and *Plutella xylostella* (Rouhani et al., 2012; Shoaib et al., 2018). The working mechanisms of Si-NPs were reported due to desiccation, body wall abrasion and spiracle blockage (Shoaib et al., 2018) and breakdown of the self-protective lipid water barrier by physico-absorption of NPs that leads to motility of pests (Rai and Ingle, 2012).

Meanwhile, Si-NPs was used by Madany et al. (2020) in controlling a root holoparasitic weed, known as branched broomrape (*Orobanche ramosa*), that affects many crops especially tomato plants. The Si-NPs treated plants were more tolerant to parasitic weed *Orobanche* infection through upregulating lignin biosynthesis that strengthened the cell wall of host roots. This would act as a physical barrier against penetration of tubercle haustorial, thus reducing the infection severity by reducing both the number and biomass of *Orobanche* tubercles. Si-NPs also dramatically enhanced the physiological and biochemical disorders performed by *Orobanche* by reducing the production of radical oxygen species (ROS) and improving production of antioxidants in roots of infected tomato (Madany et al., 2020). In other cases, Si-NP exhibited strong antimicrobial activity of plant pathogens (Khan and Siddiqui, 2020). Evidence showed that seed priming in SiO_2-NPs was more effective compare to foliar spray in managing plant pathogenic microbes such as the *Meloidogyne incognita*, *Pectobacterium betavasculorum* and *Rhizoctonia solani* **(**Rouhani et al., 2012; Shoaib et al., 2018; Madany et al., 2020). Nonetheless, the microbial suppression capability by Si-NP is concentration- and method application-dependent. For instance, seed primed in 200 mg/L of SiO_2-NPs had improved shoot and root biomass, content of chlorophyll as well as defence enzyme activities in beetroot (Khan and Siddiqui, 2020). Chitosan-NPs that induce pathogenesis-related genes in tomatoes are useful to inhibit infection by *Fusarium andiyazi* in tomatoes (Chun and Chandrasekaran, 2019). Mesoporous SiO_2-NP (20 nm) applied on foliar at 0.5 mg/mL significantly prevented lesion enlargement and improved root growth of pineapple (*Ananas comosus* L.) infected by *Phytophthora cinnamomi*. Lu et al. (2019) indicated the advantages of SiO_2-NPs in combination with others to promote self-defence of crops, health and productivity. The formulation of nanoparticles with both herbicides and/or insecticides has been reviewed by Khan (2021). Fe_3O_4-NP applied on yellow medick (*Medicago sativa*) increased the root length and chlorophyll content, and conferred resistance against powdery mildew disease caused by fungal infection (Kokina et al., 2020). NPs were also reported to increase plant immunity towards the virus. For instance, Fe_3O_4-NP foliar spray increased the biomass, antioxidant and salicylic acid content of *Nicotiana benthamiana.* Chai et al. (2020) stated that high content of endogenous salicylic acid conferred plant resistance against infection by Tobacco Mosaic Virus.

SIDE EFFECT AND RISK

Despite many advantages of NP application on plants and agriculture, excess amount and long effects of excessive application could pose a threat. A reliable method currently available to detect the presence of NPs is very limited, one of which is using inductive coupled plasma mass spectroscopy (ICP-MS) (Navratilova et al., 2015; Mahdi et al., 2017). To date, very limited study has been conducted on the detrimental effect of NPs in food (vegetables, fruits, milk, meat) and on the environment. Our current understanding is that heavy metal-derived NPs such as $AgNO_3$, Al_2O_3, CeO_2, CuO_2 and TiO_2 that are being used as fertiliser and pesticide are toxic and must be avoided (reviewed by Rastogi et al., 2017). Nevertheless, the toxicity effects of NP are dependent on the size, concentration and type of NP.

Plant responses to NP toxicity also vary among species and growth stages (Rastogi et al., 2017; 2019; Madany et al., 2020; Usman et al., 2020). A larger size and lower concentration of NP always exhibited lower toxicity compared to a smaller size and higher concentration (Cvjetko et al., 2017; Jiang et al., 2014). For instance, Ag-NP is extensively used as antimicrobial agents, detergents (shampoo, soap, toothpaste), wastewater treatment, food packaging and storage containers. The presence of Ag-NP in sludge and waste may easily reach and be absorbed by plants. Reports by Landa et al. (2016) and Tripathi et al. (2017) verified the negative impact of Ag-NP on plant physiology including their growth, productivity and pigment production. A study reported by Mazumdar and Ahmed (2011) showed that Ag-NPs at 25 nm and higher concentrations would damage the cell wall and vacuoles of root cells of rice, *Oryza sativa*. Interestingly, despite toxicity at higher concentrations, in lower concentrations (< 30 µg/mL), Ag-NPs can induce the root growth of rice (Mirzajani et al., 2013).

Copper is an essential micronutrient for proteins including enzymes to function. Cu-NPs are widely applied in commercial antimicrobial detergents, catalysts and electronic devices (Kasana et al., 2017). The study had shown that at a concentration lower than 0.25 mg/L, Cu-NPs stimulated the photosynthesis activity in *Elodea densa* (Nekrasova et al., 2011). However, a higher concentration of Cu-NPs caused damage to root morphology (Shaw et al., 2014; Song et al., 2016; Adams et al., 2017). Therefore, the application of metal-based NPs in agricultural practice should be under meticulous supervision and monitoring due to their adverse effects.

CONCLUSIONS AND FUTURE PROSPECTS

Nowadays, nanoparticles are becoming a part of our life and are intensively used. The NP concentration has increased in various plant parts, entering our food chain and the environment becoming a threat to living beings, humans and animals as well as plants. Therefore, nanoscience must attract attention and funding for awareness on the safe disposal of NP products. Superfluous metal and metal oxide-derived NPs are hazardous to plants. Nonetheless, trace quantity of NPs is beneficial for improving seed germination, growth and biomass production of plants. At high concentrations, different mechanisms negatively affect plant growth at various phases. NPs may aggregate on the surface of root which causes physical damage, alters communities of soil microbes and indirectly increases the absorption of co-contaminants in plants. At plant levels, a biochemical mechanism that causes toxicity, change the uptake of nutrients, causes genotoxicity and increases the synthesis of reactive oxygen species, subsequently decreases the activity of antioxidant enzymes, photosynthesis and gas exchange. Nonetheless, evidence also suggests that most NPs show encouraging and desirable effects at the biochemical, physiological and molecular levels, and morphological traits of the crops. The NPs impact on crop plants are dependent on the plant species, growth stage, amount and application methods as well as the duration of the exposure.

The utilisation of nontoxic NPs such as silicon/silica (Si) should be considered in agriculture. Despite the abundant presence of silicon in soil, only depolymerized mono silicic acid (SiO_4H_4) is absorbed by plants. Naturally, the origin of mono silicic acid is from weathering of soil minerals containing Si, desorption from the soil matrix and irrigation water. In solution, SiO_4H_4 maximum solubility is at 2 mM while in the soil the solution varies between 0.1 and 0.6 mM (Alsaeedi et al., 2019). The presence of Si between 0.1% and 10% of biomass weight in various plant species possesses several advantages such as helping water retention, controlling pesticides and carrier of fertilizer and pesticide (Rastogi et al. 2019; Ng et al. 2021). Furthermore, the application of green synthesis of nano-silicon is also possible. The study showed that *Bacillus* and *Trichoderma* can synthesise silicon nanoparticles. Application of microbial would also reduce dependency on the exogenous application of nanoparticles into agricultural land.

As the way forward, the challenging issues for future research are extensive study at molecular levels which is a must to understand the plant cell-NPs interactions at the early stage (Usman et al., 2020; Abarca-Cabrera et al., 2021). This would determine the critical amount of NPs that is safe for plants without showing signs of stress and toxicity (Ameen et al., 2021; Garcia-Sanchez et al., 2021). Standardised nanoparticle toxicity assays are required to evaluate both the consequences and risk of NPs on the growth, yield and food quality. It is critical to extend phytotoxicity studies of NPs on multiple generations to estimate the long-term impact thus providing a more accurate and holistic approach to the NP utilisation. Although plant response towards NPs is species-dependent, not much is known regarding the response of woody species to NPs. Lastly but not least, the interaction between miRNA and NPs in plants remains largely open for investigation.

AUTHORS CONTRIBUTION

MFNH and AA conceived and designed the work. MFNH, NLC and MSMG performed the analysis. MFNH and AA wrote the paper. MFNH, NLC, MSMG and AA checked and approved the submission.

CONFLICT OF INTEREST

All authors have read the manuscript and declare no competing interest.

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