Supporting information

Application of nano-agricultural technology for biotic stress management: mechanisms, optimization, and future perspectives

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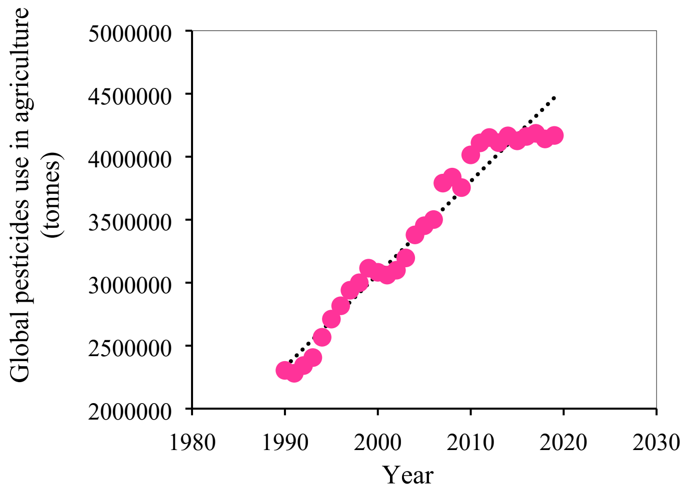

Figure S1. The global pesticides use in agriculture from 1990-2019. Source of data: FAOSTAT (http://www.fao.org/faostat/en/#data). Accessed date: 23 April 2022.

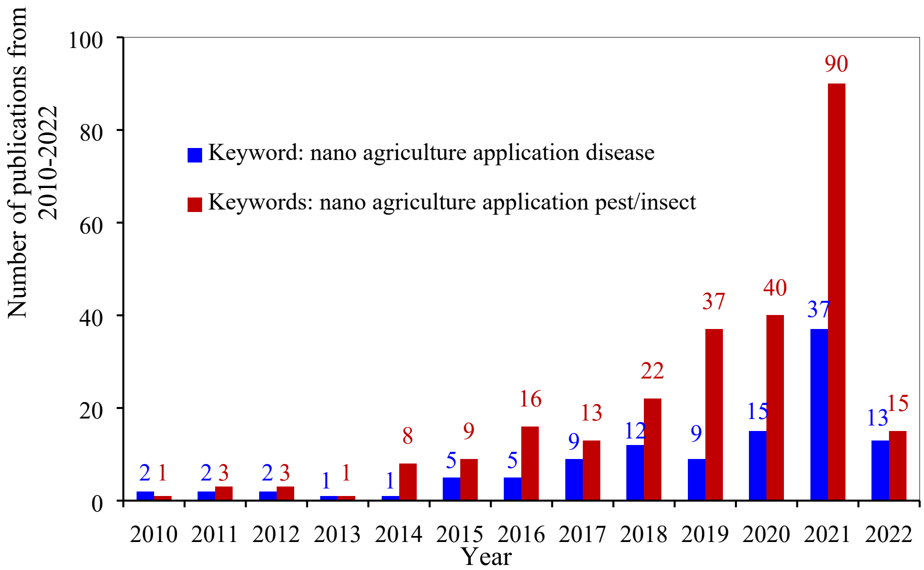

Figure S2. Number of publication related to using nano-agricultural technology in crop disease and pest control from 2010-2022. Source of data: Web of Science. Accessed date: 23 April 2022. Keywords: Nano agriculture application disease/pest/insect.

Table S1 The crop disease and pest occurrence area, prevention and control area, and induced yield loss in China mainland from 2010-2016. Source of data: Ministry of Agriculture and Rural Affairs of the People's Republic of China (http://zdscxx.moa.gov.cn:8080/nyb/pc/index.jsp). Accessed date: 23 April 2022.

Year	Crop disease and pest occurrence area (1000 hectares)	Crop disease and pest prevention and control area (1000 hectares)	Crop disease and pest induced yield loss (tons)
2010	367369.07	444919.95	16211916.37
2011	355687.06	437928.01	13591830.12
2012	384621.00	481687.00	17172212.06
2013	359533.44	445990.12	14180100.00
2014	348415.18	449141.13	13821913.28
2015	344643.94	438206.56	14186794.72
2016	321800.43	413983.21	12295833.87
Average	354581.45	444550.85	14494371.49

Table S2 Current investigations on using NMs to control crop diseases and pests.

NMs	Application method and dose	Host and pathogen/pest	Performance and mechanism	Reference
Ag^0 (size: not reported)	Foliar application; 10 and 100 mg/L	Tobacco; *Phytophthora parasitica*	The disease control efficiency of 100 mg/L Ag^0 NMs was comparable to mefenoxam (33.2 μg of active ingredient/mL). Mechanistically, Ag^0 NMs exhibited high antimicrobial activity.	Ali et al. (2015)[29]
Ag^0 (size: 18-39 nm)	Foliar application; 25, 50, 75, and 100 mg/L	Rice; *Xanthomonas oryzae* pv. *oryzae*	100 mg/L Ag^0 NMs inhibited the spread of *Xanthomonas oryzae* pv. *oryzae* in rice by 72.5%. Mechanistically, Ag^0 NMs exhibited high antimicrobial activity.	Ahmed et al. (2020)[31]
Ag^0 (size: 35 nm)	Foliar application; 30, 60, 90, 120, and 150 ppm	Castor; *Spodoptera litura* and *Helicoverpa armigera*	The antifeedant acitivity of Ag^0 NMs was significantly higher than equivalent mass Ag ions, while lower than equivalent mass Azadurachtin (commercial pesticide).	Manimegalai et al. (2022)[32]
Ag^0 (size: not reported)	Soil amendment; 20, 40, 200, 500, and 1500 mg/kg	Tomato; *Meloidogyne incognita*	Ag^0 NMs at 200 mg/kg caused 52.0% mortality of pathogenic nematodes after 3 days exposure, and the application of Ag^0 NMs showed no effect on the growth of plant and the free living nematodes.	Entsar (2016)[33]
Ag^0 (size: 7.7-50.2 nm)	Foliar application; 100 mg/L	Bean; *Bean yellow mosaic virus*	Ag^0 NMs decreased the disease severity of bean by 25.0-97.3%. Mechanistically, Ag^0 NMs exhibited high antimicrobial activity.	Elbeshehy et al. (2015)
Chitosan Schiff-based Ag^0 (size: not reported)	Foliar application; 19.2, 11.5, 5.8, and 2.9 mg/L	Tobacco; *Tobacco mosaic virus*	Chitosan Schiff-base Ag^0 NMs suppressed 72.2 % tobacco mosaic virus spread in tobacco. Mechanistically, chitosan Schiff-base Ag^0 NMs enhanced the antioxidative enzyme activity (superoxide dismutase (SOD), peroxidase (POD), hydrogen peroxidase (CAT), and phenylalanine ammonia lyase (PAL)) in tobacco.	Wang et al. (2016)[30]
Cu^0 (size: 5-50 nm)	Foliar application; 1.0, 1.5, 2.0, and 2.5 mg/L	Tea tree; *Poria hypolateritia*	Cu^0 NMs reduced the disease incidence in tea trees and enhanced their yield. Mechanistically, Cu^0 NMs exhibited high antimicrobial activity.	Ponmurugan et al. (2016)

Graphene oxide loaded CuO (size: 21.3 nm)	Foliar application; 4 and 8 mg/L	Tomato; *Pseudomonas syringae* pv. *tomato*	Graphene oxide loaded CuO NMs decreased the disease severity of tomato by 10-55%. Mechanistically, graphene oxide loaded CuO NMs exhibited high antimicrobial activity.	Li et al. (2017)[133]
Cu-chitosan (size: 150 nm)	Seed treatment; 0.01, 0.04, 0.08, 0.12, and 0.16% (w/v)	Maize; *Curvularia lunata*	Cu-chitosan NMs reduced the disease severity of maize. Mechanistically, Cu-chitosan NMs could "mimic" the natural elicitation of the plant defense and antioxidant system to enhance the host disease resistance.	Choudhary et al. (2017)
CuO (size: 30 nm)	Foliar application; 1000 mg/L	Watermelon; *Fusarium oxysporum*	CuO NMs reduced the rank sum of disease ratings of Fusarium wilt in watermelon by about 35% and enhanced the yield of watermelon by 39%-53%. Mechanistically, CuO NMs upregulated the PR gene in watermelon and enhanced the activity of PPO.	Elmer et al. (2018)[39]
CuO (size: 40 nm)	Foliar application; 500 mg/L	Chrysanthemum; *Fusarium oxysporum*	Chrysanthemum treated with CuO NMs had a 30-55% reduction in disease severity as compared with untreated plants. Mechanistically, CuO NMs provided Cu nutrient to chrysanthemum.	Elmer et al. (2021)
CuO (size: 320 nm)	Soil amendment; 31 mg Cu/kg	Lettuce; *Fusarium oxysporum*	The fresh shoot biomass of pathogen infected lettuce was significantly enhanced by the presence of CuO NMs. Mechanistically, CuO NMs enhanced the disease resistance in lettuce.	Shang et al. (2021)[129]
CuO (size: 40-80 nm)	Root irrigation; 50, 125, and 250 mg/L	Tobacco; *Ralstonia solanacearum*	The disease index of *Ralstonia solanacearum* infected tobacco was decreased from 97.3 to 38.1% after treated with 250 mg/L CuO NMs. Mechanistically, CuO NMs exhibited excellent antibacterial activity.	Chen et al. (2019)
CuO (size: 30 nm); $Cu_3(PO_4)_2$ (size: 50-610 nm)	Foliar application; 500 mg/L	Tomato; *Fusarium oxysporum*	Supplementary with $Cu_3(PO_4)_2$ and CuO NMs obviously reduced disease occurrence by 31%, with subsequent enhancing tomato growth. Mechanistically, Cu based NMs upregulated the expression of PR genes and enhanced the activity of antioxidative enzyme.	Ma et al. (2019)[41]
CuS (size: 5-10 nm)	Seed treatment and Foliar application; 50	Wheat; *Gibberella fujikuroi*	Seed soaking with 50 mg/L CuS NMs (1:4) decreased the disease incidence of bakanae disease in rice by 45.9%. Mechanistically, CuS NMs had high	Shang et al. (2020)[40]

	mg/L		antifungal ability and could active the disease resistance in wheat.	
Glycine-$Cu(OH)_2$ (size: 240 nm)	Foliar application; 200, 400, and 800 Cu mg/L	Chinese cabbage; *Xanthomonas campestris* pv. *campestris*	The disease control efficacy of glycine-$Cu(OH)_2$ NMs was >74.5%. Mechanistically, glycine-$Cu(OH)_2$ NMs exhibited high antimicrobial ability.	Dong et al. (2020)
CuO (size: 30 nm); $Cu_3(PO_4)_2$ (size: 50-610 nm)	Foliar application; 50 mg/L	Tomato; *Fusarium oxysporum*	CuO and $Cu_3(PO_4)_2$ NMs application reduced disease progress by approximately 40 and 56%. CuO and $Cu_3(PO_4)_2$ NMs could modulate crop nutrition to increase resistance to disease.	Shen et al. (2020)[42]
CuO (size: 30 nm); $Cu_3(PO_4)_2$ (size: 50-610 nm)	Foliar application; 50 and 250 mg/L	Soybean; *Fusarium virguliforme*	CuO and $Cu_3(PO_4)_2$ NMs significantly alleviated much of the pathogen infection induced soybean biomass loss. Cu based NMs upregulated the expression of PR genes and promoted antioxidative enzyme activity.	Ma et al. (2020)[17]
SiO_2 (size: not reported)	Soil amendment; 10.5 g/kg	Cucumber; *Papaya ring spot virus*	SiO_2 NMs amendment significantly reduced the disease severity of cucumber from 5.3 to 0.6. Mechanistically, SiO_2 NMs amendment enhanced the expression of PR genes and the activity of antioxidative enzyme.	Elsharkawy and Mousa (2015)
SiO_2 (size: 20 nm)	Foliar application; 100 mg/L	Tobacco; *Tobacco mosaic virus*	SiO_2 NMs application significantly decreased the relative expression of TMV-CPRNA and the accumulation of TMV protein in tobacco leaves by 79.2 and 47.3%. Mechanistically, SiO_2 NMs had antimicrobial activity and upregulated the expression of PR genes and the activity of antioxidative enzyme.	Cai et al. (2019)
SiO_2 (size: 54 nm)	Foliar application; 25-1600 mg/L	Arabidopsis; *Pseudomonas syringae*	Treatment with SiO_2 NMs (25 mg/L) resulted in a partial reduction of 29% of bacterial growth in host leaves. Mechanistically, SiO_2 NMs activated the SA dependent SAR pathway in Arabidopsis leaves.	El-Shetehy et al. (2021)[28]
SiO_2 (size: 56 nm)	Foliar application; 1500 mg/L	Watermelon; *Fusarium oxysporum f. sp. niveum*	Fast dissolving SiO_2 NMs enhanced the growth and yield of watermelon infected with *Fusarium oxysporum f. sp. niveum*. Mechanistically, fast dissolving SiO_2 NMs could sustainable and efficient provide Si nutrient for	Kang et al. (2021)[52]

			watermelon.	
Si^0 (size: 5 nm)	Foliar application; 10, 50, and 150 mg/L	Maize; *Mythimna separata*	50 mg/L Si^0 NMs significantly inhibited the growth of armyworm on maize leaf surface. Mechanistically, Si^0 NMs increased the production of chlorogenic acid in maize.	Wang et al. (2021)[54]
SiO_2 (size: 50 nm)	Foliar application; 1 and 5 mg/L	Rice; *Nilaparvata lugens Stal*	5 mg/L SiO_2 NMs application enhanced the fresh biomass of rice shoot by 61.9% in the presence of planthopper. Mechanistically, SiO_2 NMs promoted lignin formation and upregulated the expression of pest resistance related genes in rice.	Cheng et al. (2021)[53]
CeO_2 (size: 8 nm)	Soil amendment and foliar application; 50 and 250 mg/kg(L)	Tomato; *Fusarium oxysporum f. sp. lycopersici*	Disease severity was significantly reduced by soil amendment (53%) and foliar application (57%) with 250 mg/kg (L) of CeO_2 NMs.	Adisa et al. (2018)
CeO_2 (size: 54 nm)	Soil amendment; 10, 50, and 100 mg/kg	Tomato; *Helicoverpa armigera*	50 mg/kg CeO_2 NMs amendment enhanced tomato shoot biomass by 38.2% in the presence of herbivore. Mechanistically, CeO_2 NMs enhanced the defense-related compounds in tomatoes.	Xiao et al. (2021)[60]
S^0 (size: 30 nm)	Seed treatment and foliar application; 10, 30, 50, 100, and 200 mg/L	Tomato; *Fusarium oxysporum* f. sp. *lycopersici*	100 mg/L S^0 NMs significantly decreased disease occurrence by 47.6%. Mechanistically, S^0 NMs enhanced the salicylic acid content and activated SAR in tomato.	Cao et al. (2021)[19]
Carbon nanotube (diameter: 30-50nm; length: 10-20 μm), graphene (thickness: 8-12 nm;	Foliar application; carbon nanotube: 50 and 100 mg/L, graphene: 250 and 500 mg/L	Tomato; *Fusarium oxysporum*	Carbon based NMs significantly decreased the disease severity of pathogen infected tomatoes by 40-56% and increased the yield of tomato by 18-25%. Mechanistically, carbon based NMs enhanced the photosynthetic pigments, ascorbic acid and flavonoids, and the activity of the antioxidant enzymes content in tomato.	González-García et al. (2022)[66]

diameter: 2 μm)				
Nitrogen doped carbon dots (size: 2 nm)	Foliar application; 10 mg/L	Tomato; *Ralstonia solanacearum*	Nitrogen doped carbon dots application suppressed disease severity of tomato by 71.2%. Mechanistically, nitrogen doped carbon dots could direct scavenge excess ROS, enhance antioxidative enzyme activity, and active SAR in tomatoes.	Luo et al. (2021)[57]
reduced graphene oxide (thickness: 0.6-3.7 nm; diameter: 500 nm)	Foliar application; 50 and 200 mg/L	Rose; *Podosphaera pannosa*	The spread of *Podosphaera pannosa* on rose leaves was significantly suppressed by 45.9% after foliar application with 200 mg/L reduced graphene oxide. NMs exposure increased plant disease resistance through enhancing the concentration of phytohormones.	Hao et al. (2019)[46]
Chitosan (Size: not reported)	Seed treatment; 50, 100, 250, and 500 mg/kg	Pearl millet; *Sclerospora graminicola*	250 mg/kg chitosan NMs application decreased the disease incidence from 97.5 to 8.3%. Chitosan NMs enhanced host disease resistance against downy mildew through increase nitric oxide generation.	Siddaiah et al. (2018)
MgO (Size: 20 nm)	Foliar application; 100, 200, and 1000 mg/L	Tomato; *Xanthomonas perforans*	The disease severity of pathogen infected tomato in MgO NMs treatments was 12-32% less than Kocide 3000+Mancozeb treatments. Mechanistically, MgO NMs had excellent antimicrobial ability.	Liao et al. (2021)[63]
ZnO (Size:12 nm)	Foliar application; 50 and 100 mg/L	Tomato; *Tomato mosaic virus*	ZnO NMs significantly alleviated the harmful effects of ToMV infection in tomatoes. Mechanistically, ZnO NMs exhibited high antimicrobial ability and enhanced the content of enzymatic and non-enzymatic antioxidants in tomatoes.	Sofy et al. (2021)[64]
Hydroxyapatite (width: 10 nm; length:10-20 nm)	Foliar application; 9.3 and 46.5 mg P/L	Tomato; *Fusarium oxysporum*	Hydroxyapatite NMs exposure significantly increased the shoot mass of pathogen infected tomato by 40%. Mechanistically, hydroxyapatite significantly elevated PAL activity and total phenolic content in tomatoes.	Ma et al. (2021)[98]

Fe_3O_4 (Size: 20 nm)	Foliar application; 100 mg/L	Tobacco; *Tobacco mosaic virus*	The relative tobacco mosaic virus content at the transcription and protein levels was decreased from 1.00 and 1.41 to 0.33 and 0.34 after the application of Fe_3O_4 NMs. Fe_3O_4 NMs activated plant antioxidants, and upregulated SA synthesis and the expression of SA-responsive PR genes, thereby enhancing plant resistance against pathogens.	Cai et al. (2020)[62]

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