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Nanopesticides: Current status and scope for their application in agriculture

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Table S1. Efficacy of nanoemulsion and nanosuspension/nanodispersion formulations against insect-pests and pathogens

Nanoformulation/carrier	Active ingredient	Attributes	Effective against	References
Nanoemulsions				
Lecithin and Tween 80	oregano and thyme essential oil	increased efficacy	*Sitophilus oryzae*	Hossain et al. 2019
Span 80, Tween 80 and lecithin	cinnamon essential oil and thiabendazole	reduced fruit decay	*Rhizopus stolonifera* and *Botrytis cinerea*	Yousef et al. 2019
Tween 80 and lecithin	pyrethrum	enhanced activity	*Myzus persicae*	Pascual-Villalobos et al. 2019
Alkyd resin	λ-cyhalothrin	increased water stability	insects	Qin et al. 2017
Tween 80 and Span 20	clove essential oil	improved antifungal property	*Phytophthora palmivora*	Rattanapet and Aht-Ong 2019
Palm kernel oil ester	parthenium hysteropho-rus crude extract	herbicidal activity	*Diodia ocimifolia*	Zainuddin et al. 2019
Pluronic F-127, clove oil, MW 12600 and HLB 22	sulphonamides	β-carbonic anhydrase inhibition	*Leishmania infantum* and *Leishmania amazonensis*	Cardoso et al. 2018
MCT oil and Tween 80	cinnamon oil	increased stability	*Microbial pathogens*	Chuesiang et al. 2018
Tween 80	*Pimpinella anisum* essential oil	enhanced stability and efficiency	*Tribolium castaneum*	Hashem et al. 2018
Span 85, Brij 97 and ethylene glycol	citral	increased stability and extended activity	bacteria	Lu et al. 2018
Tween 80	*Satureja hortensis* essential oil	enhanced bioherbicidal activity	*Chenopodium album* and *Amaranthus retroflesus*	Hazrati et al. 2017
Gelatin-chitosan, Tween 20 and Span 60	canola oil, α-tocopherol, cinnamaldehyde and garlic oil	high antioxidant activity	*Pseudomonas aeruginosa*	Pérez-Córdoba et al. 2018
Glycerol, Tween 80 and Agnique BL1754	tebuconazole	increased stability	–	Díaz-Blancas et al. 2016
Tween 20	*Simmondasia chinensis* oil	high mortality	*Sitophilus oryzae*	Abouelkassem et al. 2016
Lemon essential oil, sur-factant, Tween 20 and glycerol	pyrethrin	dose reduction	*Aphis gossypii*	Kalaitzaki et al. 2015
Octyldodecyl myristate and polysorbate 80	*Manilkara subsericea* crude extract	non-target safety	*Dysdercus peruvianus*	Fernandes et al. 2014
Aqueous filtrate of *Pongamia glabra* and *Jatropha curcas*	*Eucalyptus globules* oil	enhanced toxicity	*Tribolium castaneum*	Pant et al. 2014
N-butyl acetate, ammo-nium glycyrrhizinate and sec-butyl alcohol	permethrin	greater efficacy and reduced effects on non-target organism	*Aedes aegypti*	Kumar et al. 2013
Tween 20	neem oil	enhanced toxicity	*Culex quinquefasciatus*	Anjali et al. 2012
Fatty acid methyl esters, SAPG, LAPG and organosilicone	glyphosate isopropylamine	enhanced leaf wettability, penetration and toxicity	*Eleusine indica*	Jiang et al. 2012
Methyl decanoate and polyoxyethylene lauryl ether	β-cypermethrin	increased stability	–	Wang et al. 2007
Nanosuspension/nanodispersion				
Polycarboxylate and MRES and sucrose	abamectin	enhanced bioavailability	*Plutella xylostella*	Cui et al. 2019

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Table S1 to be continued

Nanoformulation/carrier	Active ingredient	Attributes	Effective against	References
Emulsifier 700	lambda-cyhalothrin	reduced amount of surfactants	*Lipaphis erysami*	Wang et al. 2019a
Ethyl acetate, emulsifier 1601, emulsifier 600 and lactose	lambda-cyhalothrin	enhanced stability	*Myzus persicae*	Wang et al. 2019b
Sodium alginate and Tween 80	pyridalyl	enhanced toxicity	*Helicoverpa armigera*	Saini et al. 2014
N-butyl acetate, ammonium glycyrrhizinate, sec-butyl alcohol and sucrose	permethrin	reduced dose	*Culex quinquefasciatus*	Anjali et al. 2010
Isobutyl acetate, isopropanol and surfactants	novaluron	nanosize and high efficiency	*Spodoptera littoralis*	Elek et al. 2010
Cyclohexanone and *N*,*N*-dimethylformamide	β-cypermethrin	high drug loading capacity and controlled release	–	Zeng et al. 2008

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Table S2. Efficacy of polymer-based pesticide nanoformulations against insect-pests, pathogens and weeds

Nanoformulation/carrier	Active ingredient(s)	Attributes	Target organism(s)	References
Polymer nanoencapsulations				
Methoxy poly(ethylene glycol)-*b*-poly(lactide-*co*-glycolide)	metolachlor	water solubility, sustained release	*Oryza sativa* and *Digitaria sanguinalis*	Tong et al. 2017
Poly(ε-caprolactone)	carbendazim and tebuconazole	sustained release	–	Campos et al. 2015
Silica–epichlorohydrin–carboxymethylcellulose	emamectin benzoate	enzyme responsive with reduced genotoxicity	*Myzus persicae*	Guo et al. 2015
Sodium alginate and chitosan	acetamipirid	controlled release	–	Kumar et al. 2015
Poly(lactic-*co*-glycolic acid)	imidacloprid	reduced dose with enhanced effectivity	*Diaphorina citri*	Meyer et al. 2015
Poly(ethylene glycol) 6 000	temephos and imidacloprid	enhanced toxicity and reduced dose	*Culex quinquefasciatus*	Bhan et al. 2014
Poly(ε-caprolactone), Tween 80 and Span 60	ametryn and atrazine	reduced dose	weeds	Clemente et al. 2014
Poly(ε-caprolactone) and chitosan	atrazine	improved adhesion and slow release	–	Grillo et al. 2014
Polydopamine	avermectin	sustained and controlled release	–	Jia et al. 2014
Sodium alginate	imidacloprid	better efficacy	*Amrasca* spp.	Kumar et al. 2014
Poly(citric acid) and poly(ethylene glycol)	imidacloprid	increased release rate and better performance	*Glyphodes pyloalis*	Memarizadeh 2014; Naeini et al. 2010
Poly(ε-caprolactone)	atrazine	target specific with increased toxicity	*Brassica* spp.	Pereira et al. 2014
Carbon nanotubes with hyperbranched polycitric acid	mancozeb and zineb	increased contact area	*Alternaria alternate*	Sarlak et al. 2014
Carboxymethyl chitosan	methomyl	reduced UV-degradation	*Mythimna separata*	Sun et al. 2014
Poly(ethylene glycol) 400	acephate	increased controlled and targeted delivery	*Oligonychus coffeae*, *Spodoptera litura*, *Lipaphis erysimi* and *Bemisia tabaci*	Pradhan et al. 2013
Poly(ethylene glycol) 400	acephate	water solubility and reduced toxicity	–	Choudhury et al. 2012
Polyethylene glycol and polybutylene adipate	*Onopordon leptolepis* extract	controlled release	bacteria and fungi	Esmaeili and Saremnia 2012
Poly(ε-caprolactone) and chitosan	ametryn, atrazine, and simazine	increased stability and controlled release	*Allium cepa*	Grillo et al. 2012
Methyl methacrylate-styrene	lansiumamide B	better efficacy	*Bursaphelenehus xylophilus* and *Meloidogyne incognita*	Yin et al. 2012
Poly(ethylene glycol) 6 000	*Allium sativum* essential oil	sustained release	*Tribolium castaneum*	Yang et al. 2009
Sodium alginate and chitosan	imidacloprid	increased toxicity	*Martianus dermestoides*	Guan et al. 2008
Nanospheres				
Attapulgite, NH_4HCO_3, amino silicon oil, poly(vinyl alcohol) and glyphosate	glyphosate	temperature responsive controlled release	weeds	Chi et al. 2017
Polyvinyl alcohol and polyoxyethylene castor oil (EL-40)	emamectin benzoate	slow release and reduced photo degradation	insects	Wang et al. 2017
Poly(ε-caprolactone)	azadirachtin	reduced UV-degradation	*Zabrotes subfasciatus*	da Costa et al. 2014

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Table S2 to be continued

Nanoformulation/carrier	Active ingredient(s)	Attributes	Target organism(s)	References
Poly(ethylene glycol) 600, 1 000, 1 500 and 2 000	thiram	controlled release	fungi	Kaushik et al. 2013
Poly(ethylene glycol) 600 and 900	carbofuran	controlled release	*Meloidogyne incognita*	Pankaj et al. 2012
Poly(ethylene glycol) 1 000, 2 000 and 4 000	thiamethoxam	controlled release	insects	Sarkar et al. 2012
Gelatin and methyl methacrylate	tebuconazole	reduced leaching losses	*Gloeophyllum trabeum*	Salma et al. 2010
Poly(acrylic acid)-*b*-poly(butyl acrylate) and poly(styrene)-*b*-poly(ethyleneoxide)	bifenthrin	increased stability	insects	Liu et al. 2008
Nanogels				
Poly(ethylene glycol)-poly(lactic acid)-dimethacrylate	small interfering RNA (siRNA)	sustained release	–	Wang et al. 2018
Carboxymethyl cellulose, citric acid and bentonite	thiamethoxam	higher release rate	insects	Sarkar and Singh 2017
β-cyclodextrin	permethrin	reduced biodegradation	*Tineola bisselliella* and *Anthrenocerus australis*	Kettel et al. 2014
Myristic acid-chitosan	*Carum copticum* essential oil	increased toxicity and persistence	*Sitophilus garnarius* and *Tribolium confusum*	Ziaee et al. 2014
Low molecular mass gelators	methyl eugenol	reduced volatilization losses and extended release	*Bactrocera dorsalis*	Bhagat et al. 2013
Chitosan	copper (ii)	high loading and synergistic effect	*Fusarium graminearum*	Brunel et al. 2013
Poly(ε-caprolactone), Span 60 and Tween 80	*Azadirachta indica* extract	enhanced toxicity	*Plutella xylostella*	Forim et al. 2013
Chitosan and cashew gum	*Lippia sidoides* oil	enhanced loading capacity and sustained release	*Stegomyia aegypti*	Abreu et al. 2012
Polyacrylamide methylcellulose	paraquat	extended release	weeds	Aouada et al. 2011
Chitosan and cashew gum	*Lippia sidoides* oil	increased efficiency	*Aedes aegypti*	Paula et al. 2011
Sodium alginate	isoproturon, imidacloprid, and cyromazine	extended release	insects and weeds	Garrido-Herrera et al. 2006
Micelles				
Carboxymethyl chitosan and 2-nitrobenzyl	diuron	photo controlled sustained release	weeds	Ye et al. 2015
Chitin with polylactide and 1,2-dipalmitoyl-*sn*-glycero-3-phosphoethanolamine	chlorpyrifos	increased loading capacity and sustained release	insects	Zhang et al. 2013
Poly(ethylene glycol) 300, 600, 1 000 and dicarboxylic acids	imidacloprid	controlled and sustained release	insects and nematodes	Adak et al. 2012
Ricinoleic acid-grafted CMCS	azadirachtin	enhanced toxicity	insects	Feng and Peng 2012
Poly(ethylene glycol) 1 500 and 2 000	β-cyfluthrin	slow release and sustained control	*Callosobruchus maculatus*	Loha et al. 2012
Chitosan with polylactide	imidacloprid	increased loading capacity and sustained release	insects	Li et al. 2011
Poly-[poly-(oxyethylene 600/1 000/1 500/2 000)-oxyiso-phthaloyl]	β-cyfluthrin	controlled release	insects	Loha et al. 2011

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Nanoformulation/carrier	Active ingredient(s)	Attributes	Target organism(s)	References
Poly(ethylene glycol) 600, 900, 1 500 and 1 800	azadirachtin A	controlled release	insects	Kumar et al. 2010
N-(octadecanol-1-glycidyl ether)-*O*-sulfate chitosan	rotenone	increased solubility	insects	Lao et al. 2010
Poly[poly(oxyethylene 18 000)-oxy-5-decanyloxyiso-phthaloyl]	carbofuran	slow and sustained release	insects and nematodes	Shakil et al. 2010
Nanofibers				
Poly(lactic acid)/cellulose	thiamethoxam	controlled release	*Trialeurodes vaporariorum*	Xiang et al. 2013
Polyamide 6 and cellulose acetate	(*Z*)-9-dodecenyl acetate	extended release	lepidopterous moths	Hellmann et al. 2011
Chitosan nanoparticles based formulations				
Chitosan and laminarian	–	downy mildew control	*Plasmopara viticola*	Garde-Cerdán et al. 2017
Chitosan	imazapic and imazapyr	reduced toxicity	weeds	Maruyama et al. 2016
Chitosan and tripolyphosphate	Cu(II) ion	decreased disease severity	*Alternaria solani* and *Fusarium oxysporum*	Saharan et al. 2013
Chitosan	pyrifluquinazon	high efficiency and no non-target toxicity	*Myzus persicae*	Kang et al. 2012
Chitosan	saponin	spore germination inhibition	*Alternaria alternata*	Lanzotti et al. 2012a,b
Chitosan	capsaicin	high loading efficiency and controlled release	–	Feng and Zhang 2011
Chitosan	etofenprox	controlled release	*Spodoptera litura*	Hwang et al. 2011

Table S3. Efficacy of lipid-based pesticide nanoformulations against insect-pests and pathogens

Nanoformulation/carrier	Active ingredient	Attributes	Effective against	References
Glyceryl tripalmitate	carbendazim and tebu-conazole	physical stability and controlled release	–	Campos et al. 2015
Glycerol tripalmitate	atrazine and simazine	controlled release profile	*Raphanus raphanistrum*	de Oliveira et al. 2015
Nanoliposomes	*Eucalyptus citriodora* oil	stimuli responsive release	*Staphylococcus aureus*	Lin et al. 2015
Poly(butyl meth-acrylate-diacetone acrylamide)	acetochlor	slow release	–	Guo et al. 2014
Corn oil and beeswax	deltamethrin	decreased photodegradation	–	Nguyen et al. 2012
Liposomes	etofenprox	controlled release	–	Bang et al. 2009
Compritol 888 ATO and Poloxamer 188 or Miranol Ultra C32	*Artemisia arborescens* essential oil	physical stability and controlled release	*Bemisia tabaci*, *Aphis gossipy* and *Lymantria dispar*	Lai et al. 2006

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Table S4. Efficacy of clay-based pesticide nanoformulations against insect-pests, pathogens and weeds

Nanoformulation/carrier	Active ingredient	Attributes	Effective against	References
Modified clay nanoparticles	alachlor, acetochlor, metolachlor and metolachlor	enhanced adsorption	weeds	Rodrigues et al. 2013
Zinc-aluminum-layered double hydroxide	3,4-D	slow and extended release	weeds	Ghazali et al. 2013
Modified montmorillonite clay	ethofumesate	enhanced biodegradation and slow release	weeds	Chevillard et al. 2012
Nanoclay	thymol	extended release	insects and bacteria	Lim et al. 2010
Layered double hydroxide	cinnamate	slow and extended release	*Phytophthora capsici*	Park et al. 2010
Bentonite, kaolinite and Fuller's earth	carbofuran	extended release	–	Choudhary et al. 2006
Arizona montmorillonite clay	2,4-D	slow release	–	Hermosin et al. 2006
Layered double hydroxide	2,4-D	controlled release	weeds	Bin Hussein et al. 2005
Wyoming and arizona montmorillonite clays	hexazinone	reduced leaching losses	–	Celis et al. 2002

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Table S5. Efficacy of silica-based pesticide nanoformulations against insect-pests pathogens and weeds

Nanoformulation/carrier	Active ingredient	Attributes	Effective against	References
Mesoporous silica NPs	2,4-D sodium salt	enhanced pesticide loading	–	Cao et al. 2018
Silica microcapsules	kasugamycin	improved photo-thermal stability and enhanced loading efficiency	–	Fan et al. 2017
Mesoporous silica NPs	chlorantraniliprole	enhanced pesticide loading	*Plutella xylostella*	Kaziem et al. 2017
Silica cross-linked microcapsules	pendimethalin	extended release	*Amaranthus retroflexus* and *Echinochloa crussgalli*	Liang et al. 2017
Silica nanostructures	neem oil	enhanced stability and high antioxidant capacity	*Acromyrmex crassispinus*	Mattos et al. 2017
Modified silica NPs	chitinase (Chi9602)	enhanced nematicidal activity	*Caenorhabditis elegans*	Qin et al. 2016
Amino-modified silica	kasugamycin	reduced photodegradation	*E. coli*	Ding et al. 2014
Silica NPs	–	higher disease resistance in maize	*Fusarium oxysporum* and *Aspergillus niger*	Suriyaprabha et al. 2013
Silica NPs	linalool	enhanced antifeedant potential	*Spodoptera litura* and *Achaea janata*	Usha Rani et al. 2014
Silica nanocapsules	fipronil	controlled release	termites	Wibowo et al. 2014
Silica-based microcapsules	prochloraz	reduced UV degradation and slow release	fungal diseases	Zhang et al. 2014
Nanonized diatomaceous earth	–	malformation in mouthparts and mid-gut morphology of the insects	*Heteracris littorali*s	Ebeid et al. 2013
Nanosilica	–	antifeedant	*Spodoptera littoralis*	El-Bendary and El-Helaly 2013
Mesoporous silica NPs	metalaxyl	controlled release in soil	–	Wanyika 2013
Mesoporous silica NPs	imidacloprid	controlled release	termites	Popat et al. 2012
Silica NPs	chlorfenapyr	increased biological efficacy	*Plutella xylostella*	Song et al. 2012
Amorphous hydrophilic, hydrophobic and lipophilic silica NPs	–	increased effectiveness	*Sitophilus oryzae*	Debnath et al. 2011; Rahman et al. 2009; Barik et al. 2008
Carboxyl-modified mesoporous silica	2,4-D and picloram	controlled release	crop weeds	Prado et al. 2011
Amorphous nanosilica	–	enhanced cuticular absorption	*Sitophilus oryzae, Tribolium castaneum, Spodoptera litura* and *Lipaphis pseudobrassicae*	Goswami et al. 2010
Surface charged modified hydrophobic silica	–	decrease fungal growth and enhanced germination of cereal seeds	many agricultural pests	Robinson and Salejova-Zadrazilova 2010; Ulrichs et al. 2006
Porous hollow silica NPs	avermectin	protection from UV degradation and slow release	-	Li et al. 2007
Porous hollow silica NPs	validamycin	sustained release profile	bacteria and fungi	Liu et al. 2006
Lipophilic silica-based	–	enhanced physiosorption through cuticle	agricultural insect pests	Ulrichs et al. 2005; Mewis and Ulrichs 2001

NPs – nanoparticles

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Table S6. Efficacy of metal nanoparticles (NPs) as active ingredients and their nanoformulations against insect-pests and pathogens

Nanoformulation/carrier	Active ingredient(s)	Attributes	Target organism(s)	References
Silver nanoparticles (AgNPs)				
AgNPs	–	fungal germination and growth inhibition	*Sclerotinia sclerotiorum*	Guilger et al. 2017
AgNPs	cyhalothrin	increased potency and delivery efficiency	*Culex pipiens*	Abouelkassem et al. 2016
Ag-dsDNA-GO	–	antibacterial activity	*Xanthomonas euvesicatoria*, *X. gardneri*, *X. perforans*, and *X. vesicatoria*	Strayer et al. 2016
AgNPs	–	antiviral agent	Bean Yellow Mosaic Virus	Elbeshehy et al. 2015
AgNPs	*Spatoglossum asperum* and *Hedophyllum* sessile extracts	antibacterial activity	*Xanthomonas axonopodis* pv. *citri* and *X. oryzae* pv. *oryzae*	Jothirethinam et al. 2015
Spherical to polyhedral shaped AgNPs	–	larvicidal effect	*Aedes aegypti*	Vimala et al. 2015
Spherical AgNPs	–	reduction in disease severity	*Bipolaris sorokiniana*	Mishra et al. 2014
AgNPs	–	larvicidal and pupicidal activity	*Aedes aegypti*	Sundaravadivelan and Padmanabhan 2014
AgNPs	–	antifungal activity	*Fusarium oxysporum*	Gopinath and Velusamy 2013
AgNPs	–	antibacterial and antifungal activity	*Pseudomonas flavescens*, *Erwinia amylovora*, *Fusarium solani*, *F. oxysporum*, *Rhizoctonia solani*, *Helminthosporium* spp., *Alternaria alternate* and *Sclerotinia sclerotiorum*	Hafez and Kabeil 2013
DNA-directed AgNPs grown on graphene oxide	–	reduction in severity of bacterial spot disease	*Xanthomonas perforans*	Ocsoy et al. 2013
AgNPs	–	antibacterial activity	18 plant pathogens	Kim et al. 2012
Silver and gold NPs	–	high mortality	*Aedes aegypti*	Soni and Prakash 2012
Colloidal silver NPs	–	delayed growth of fungi	*Colletotrichum gloesporioides*	Aguilar-Méndez et al. 2011
AgNPs aqueous liquids	–	antifungal activity	*Sclerotium cepivorum*	Jung et al. 2010
AgNPs	–	reduced spore germination	*Fusarium culmorum*	Kasprowicz et al. 2010
AgNPs	–	antimicrobial activity	*Vibrio cholera* and *Escherichia coli*	Krishnaraj et al. 2010
AgNPs	–	high antimicrobial activity	*Bipolaris sorokiniana* and *Magnaporthe grisea*	Jo et al. 2009
AgNPs	–	antifungal activity	*Raffaelea* spp.	Kim et al. 2009
AgNPs	–	growth inhibition	*Rhizoctonia solani*, *Sclerotinia sclerotiorum* and *S. minor*	Min et al. 2009
AgNPs colloidal solution	–	antifungal properties	*Podosphaera pannosa*	Kim et al. 2008
Copper nanoparticles (CuNPs)				
Cu_2ONPs	–	antifungal activity	*Saccharomyces cerevisiae*	Giannousi et al. 2014

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Nanoformulation/carrier	Active ingredient(s)	Attributes	Target organism(s)	References
CuNPs	–	novel antifungal activity	*Curvularia lunata*, *Phoma destructive* and *Alternaria alternate*	Kanhed et al. 2014
CuNPs	–	antibacterial properties	*Xanthomonas axonopodis* pv. *punicae*	Mondal and Mani 2012
CuNPs	–	antimicrobial activity	*Escherichia coli*, *Staphylococcus aureus*, *Micrococcus luteus*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Aspergillus flavus*, *A. niger*, *Candida albicans*	Ramyadevi et al. 2012
CuNPs	–	herbicidal properties	*Elodea densa*	Nekrasova et al. 2011
CuNPs	–	antibacterial properties	*Xanthomonas campestris* pv. *phasolei* and *Xanthomonas oryzae* pv. *oryzae*	Mondal et al. 2010; Mondal and Mani 2009
Spherical CuNPs	–	antimicrobial activity	*Escherichia coli*, *Bacillis subtilis* and *Staphylococcus aureus*	Ruparelia et al. 2008
Titanium dioxide nanoperticles (TiO_2NPs)				
Ag doped hollow TiO_2 nanoparticles	–	enhanced fungicidal activity	*Fusarium solani* and *Venturia inaequalis*	Boxi et al. 2016
TiO_2NPs and TiO_2NPs doped with zinc and silver	–	antibacterial activity	*Xanthomonas perforans*	Paret et al. 2013a,b
TiO_2NPs	–	antibacterial activity	*Xanthomonas hortorum* pv. *pelargonii* and *Xanthomonas axonopodis* pv. *poinsettiicola*	Norman and Chen 2011
Other metal and non-metal nanoparticles				
Zinc oxide nanoparticles (ZnONPs)	thiram	synergistic antifungal activity	*Phytophthora capsici*	Xue et al. 2014
Nano-sulphur	–	increased efficacy against powdery mildew	*Erysiphe cichoracearum*	Gogoi et al. 2013
ZnONPs	–	prevention of conidiophores and conidial development and death of fungal hyphae	*Botrytis cinerea* and *Penicillium expansum*	He et al. 2011
Nano-sized calcium carbonate	validamycin	enhanced loading efficiency, stability and sustained release	*Rhizoctonia solani*	Qian et al. 2011

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