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REVIEW ARTICLE

Chitosan-only nanoparticles against phytopathogenic fungi in the past decade (2013–2023)

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Abstract

Chitosan is a biocompatible, biodegradable, and antimicrobial polymer. Researchers have recently explored using chitosan nanoparticles to fight phytopathogenic fungi. This review aims to provide a comprehensive overview of studies conducted between 2013 and 2023 using the most popular databases for academic research on this topic. A systematic review was conducted using Software Rayyan to support the process. The search was conducted using the Web of Science, Scopus, and ScienceDirect databases. Out of the 752 records found from 2013–2023, only 83 articles were considered eligible for inclusion in the review after screening with inclusion and exclusion criteria. Most studies showed that chitosan nanoparticles are produced using sodium tripolyphosphate (TPP) through ionotropic gelation. However, using TPP has potential drawbacks and may have a synergistic effect with chitosan, which requires further investigation. TPP can affect the biological activity of the nanoparticle matrix. Furthermore, less than 10 out of the 83 articles reviewed in the time frame explored chitosan-only nanoparticles (nanochitosan) against phytopathogenic fungi. This shows the need for more research to determine the potential benefits of chitosan-only nanoparticles in control phytopathogenic fungi.

Keywords

Antifungal, Nanochitosan, Nanoparticles, Sodium tripolyphosphate

Introduction

The biocompatibility, biodegradability, and antimicrobial activity of chitosan have led to its evaluation in various formulations for use in agriculture, food production, and crop protection against pathogens. For the year 2023, 9,767 papers were retrieved from the Web of Science Core Collection using your search engine, showing the extensive body of research attesting to the many advantages of these polymers across several domains (Table 1). Nanotechnology is a relatively new scientific field (Haris et al. 2023) that focuses on reducing the particle size of materials to the nanoscale of 1–100 nm while also enhancing their biological activity (Ansari 2023; Malik et al. 2023). It is essential to note that in polymeric systems, the definition of nanoparticle generally extends up to 1000 nm size (Jonassen et al. 2012; Zielińska et al. 2020; Lang et al. 2021). Current scholarly progress includes the development of novel agricultural goods that shield plants from pathogens (Ansari 2023), as well as the creation of complex nanoparticles based on chitosan and nanochitosan (chitosan-only nanoparticles) because the nanoscale increases inhibition against fungi pathogens

(Kheiri et al. 2016; El-Mohamedy et al. 2019). However, there is knowledge to be generated; for example, when changing the search for chitosan to nanochitosan and chitosan nanoparticles, 246 articles were found during the past decade (only 24 in 2023) according to the Web of Science search engine. Based on the 17 goals of the United Nations' Sustainable Development 2030 Agenda, the number of agriculture-related articles was reduced (see Table 2). There is a significant potential to assess the benefits and drawbacks of applying nanochitosan in crop protection. This literature analysis aimed to provide a comprehensive overview of studies conducted between 2013 and 2023 to assess the existing understanding of nanochitosan in phytopathogenic fungi, particularly to find research on nanoparticles composed exclusively of chitosan.

Table 1. Results from the Web Science search engine with entry information on chitosan with filter year 2023.

Document Type	Record Count	% of 9,767
Article	8,449	86.51
Review Article	1,210	12.39
Early Access	1,070	10.95
Correction	43	0.44
Meeting Abstract	32	0.33
Book Chapters	12	0.12
Proceeding Paper	12	0.12
Editorial Material	10	0.10
Letter	8	0.08
Retraction	6	0.06
Expression Of Concern	1	0.01

Data from the Web of Science. The search was performed at 9:45 AM (Pacific Time) on 12/14/2023.

Table 2. Results of articles related to some Sustainable Development Goals and closely linked to agriculture from the Web Science search engine using the keywords nanochitosan and chitosan nanoparticles (2013–2023).

Sustainable Development Goals	Record Count	% of 246	closely linked to agriculture
03 Good Health and Well Being	78	31.71	
06 Clean Water and Sanitation	48	19.51	
11 Sustainable Cities and Communities	41	16.67	
14 Life Below Water	7	2.85	
02 Zero Hunger	5	2.03	✓
13 Climate Action	2	0.81	
12 Responsible Consumption and Production	1	0.41	✓
15 Life on Land	1	0.4 1	✓

Data from the Web of Science. The search was performed at 9:40 AM (Pacific Time) from 12/14/2023.

Methods

To be considered for inclusion in this review, papers had to have been retrieved from the databases ScienceDirect, Web of Science, and Scopus. A search approach combines the keywords "chitosan nanoparticles", "nanochitosan", "fungi", and "fungal". The Boolean operators "OR" and "AND" were used for a more precise search with the following nomenclature: [chitosan nanoparticles OR nanochitosan] AND [fungi OR fungal]. Then, the results were filtered. First, the duplicate articles were removed. Later, records were excluded based on specific selection criteria with information in the titles and abstract. The criteria for inclusion were: (1) only research papers; reviews and chapters were excluded; (2) Articles had to have been published between 2013 and 2023; (3) Articles had to be written in the English language. Also, exclusion criteria encompassed research or models devoid of fungus and studies including yeast. The management of articles was supported by Software Rayyan (Free Plan) (Ouzzani et al. 2016). Other references were included to supply further explanations or to present varying viewpoints on particular subjects.

Results and discussion

Fig. 1 illustrates the number of papers that evaluated the efficacy of chitosan nanoparticles against phytopathogenic fungi. These publications were disseminated through

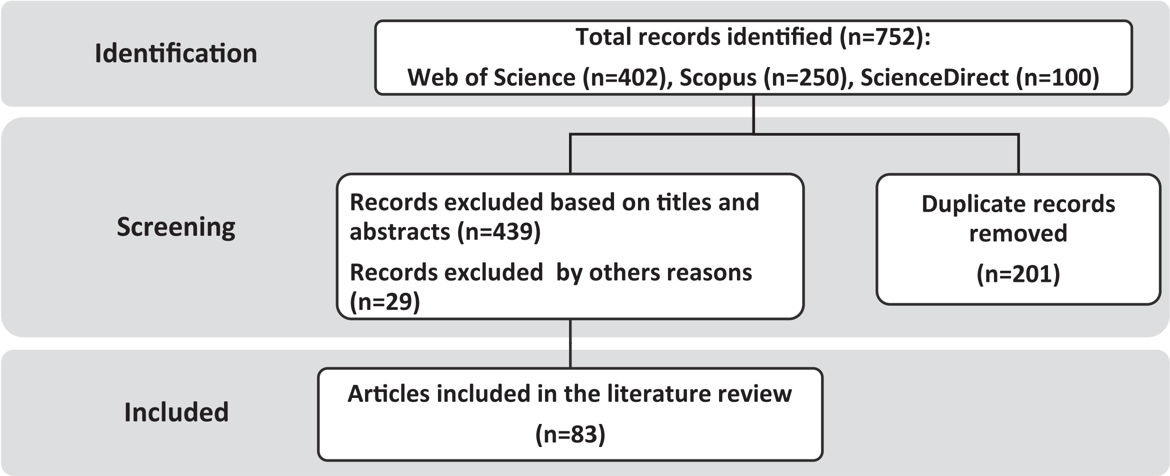

Figure 1. Flow diagram with results of articles used in the review.

the Web of Science, Scopus, and ScienceDirect databases from 2013 to 2023. Of the 83 studies reviewed, 47 (56%) used sodium tripolyphosphate (TPP) to create chitosan nanoparticles. The ionotropic gelation method (IG) was the most used. The resulting particle sizes were mainly less than 400 nm, as reported in Tables 3, 4. Additionally, 29 out of the 47 studies (more than 50%) that used TPP examined the nanoparticles for potential use as carriers of other molecules or substances to enhance the effectiveness of chitosan.

Compounds such as metals, fungicides, essential oils, and vegetable extracts (mostly alcoholic) are examples of molecules or substances for carriers or mixed with chitosan-TPP (Table 4). The most described method for preparing chitosan nanoparticles in the literature is the TPP method, which is simple and easy to use (Bugnicourt and Ladavière 2016). This review shows that this tendency persisted until 2023. Sometimes, the word TPP is left out from the title or abstract of certain articles. This can give the impression that the discussed nanoparticles are made solely of chitosan. However, upon closer examination of the method used to create the nanoparticles, it becomes clear that IG or some other method involving TPP is used.

Chitosan-TPP and nanochitosan

The omission of TPP in the titles and abstracts maybe because it is the most used compound for producing chitosan nanoparticles and is considered safe. However, Hsissou et al. (2021) describe a composite material as "*the assembly of two or more materials, the final assembly having properties superior to the properties of each of the constituent materials*." Also, Zweben (2024) defines composite as "*two or more materials bonded together, have revolutionary properties compared to traditional monolithic materials*," and Fakirov (2015) explains, "*Polymer–polymer composites are then such composites whose reinforcement and matrix belong to two chemically different materials*." To distinguish it from nanoparticles made from chitosan alone, it is important to name the matrix chitosan-TPP as a nanocomposite rather than nanochitosan. The word nanochitosan should be used for particles made with chitosan-only. Although chitosan is the primary component in chitosan-TPP, and it could be argued that its biological activity is solely due to chitosan, it is still possible that there is a synergistic effect between chitosan and TPP. Koukaras et al. (2012) have reported that chitosan-TPP contains mostly chitosan, but it is essential to recognize the potential contribution of TPP to the overall biological activity of the nanocomposite.

TPP synergistic effect

Sodium tripolyphosphate ($Na_5P_3O_{10}$) (TPP) is a crystalline inorganic salt anionic that belongs to the group of condensed phosphates and is used mainly for the industry of detergents (Makara et al. 2016). Also, it is widely used in the IG method to cross-link polycationic polymers, and the elaboration of chitosan nanoparticles is not the exception for being considered physiologically nontoxic (Rampino et al. 2013; Dmour and Taha 2018). The nanoparticles of chitosan-TPP are a consequence of the ionic interaction between amino groups ($\text{-NH}^{+\,3}$) of chitosan and phosphate groups of TPP ($\text{-P}_3\text{O}^{-5}_{10}$) and particle formed contend phosphorus in the structure (Antoniou et al. 2015; Sarkar et al. 2022). It is possible that some authors do not use TPP controls due to its low content compared to chitosan and the limited activity of TPP because of ionic interactions with chitosan (Rampino et al. 2013).

Mondéjar-López et al. (2022) show that chitosan-TPP nanoparticles do not impede the germination of wheat, barley, and oats seeds, and the potential exists for chitosan-TPP-fungicide nanoparticles to mitigate the phytotoxic impact of pure fungicides on plants, although in certain circumstances (Maluin et al. 2020). On the contrary, the study conducted by Asgari-Targhi et al. (2018) reveals that the growth and development of *Capsicum annuum* were significantly inhibited by chitosan-TPP nanoparticles (5, 10, and 20 mg L^{-1}). Wang et al. (2021) found that the impact of TPP varied, with positive or negative effects contingent upon the plant organ; specifically, the authors reported that TPP promoted leaf development while impeding stem growth. On the other hand, Chouhan et al. (2022) report that kidney cells were altered from a concentration of 0.3 mg/mL chitosan-TPP nanoparticles to give a negative response and cause reproductive inability. Divya et al. (2018) reported on the cytotoxicity activity of fibroblast cells. They measured the percentage of viable cells and percent cytotoxicity. After 24 hours of incubation, 300 mg/mL killed 74.16% of the cells, obtaining an LD_{50} value of 64.21 mg/mL. Moreover, few researchers, such as Xiong et al. (2023) and Cota-Arriola et al. (2013), have evaluated or discussed this possible synergistic biological activity between chitosan and TPP. Earlier reports have shown that TPP has antifungal activity against fungi phytopathogens (Knabel et al. 1991; Cota-Arriola et al. 2013; Jakovljevic et al. 2014). These reports suggest that the effects of chitosan-TPP nanoparticles could be governed by a synergistic, which can have a positive or negative impact depending on the interacting organism of the nanoparticle. Further studies are needed to determine the full range of potential disadvantages of chitosan-TPP nanoparticles against fungal phytopathogens.

The effects of the TPP component after the breakdown of chitosan-TPP nanoparticles are unclear. This review cannot answer concerns about residual TPP accumulation and its potential impact on non-target organisms. Previously, Palmeira-de-Oliveira et al. (2011) reported that the overall *in vitro* activity of TPP has not been investigated. However, several studies have shown that the environmental problem known as eutrophication and changes in proteases and protein fungal activity can be generated with the used TPP (Stojanović et al. 2010; Stojanović et al. 2011; Jakovljević et al. 2020). To avoid these negative effects, it is recommended to seek alter-

Table 3. List of research studies conducted between 2013 and 2023 that evaluated the efficacy of Chitosan-TPP nanoparticles against phytopathogenic fungi.

#	Reference	Fungal	Crop	Characteristic nanoparticle		Major findings for this review
				Size (nm)	Potential Z (mV)	
1	El-Mohamedy et al. (2019)	*Alternaria solani* *Botryties cinerea* *Fusarium oxysporium* *Fusarium sembaticum* *Fusarium solani* *Macrophomina phaseolin* *Phytophthora infestance* *Rhizoctonia solani* *Sclerotina. Sclerotiorum* *Sclerotium rolfsii*	Tomato Potato Green bean	40–70	48	Concentrations 0.1% and 0.05% showed completely inhibited (100%) the mycelial growth of all tested pathogens
2	Sarkar et al. (2022)	*Alternaria alternata*	*Capsicum annuum L.*	<100	---	100% inhibition to 0.1%
3	Izadi et al. (2021)		Tomato	150	32	Antifungal activity
4	Sen et al. (2022)	*Aspergillus flavus*	Mung bean [*Vigna radiata* (L.) R. Wilczek]	~260	100	Inhibition spore germination
5	Singh et al. (2020a)		---	40–100	41	Low effects antifungal
6	Elshaer et al. (2022)	*Aspergillus niger*	---	216–263	----	MIC:256.0 μg/mL MFC: 512.0 μg/mL
7	Hasheminejad et al. (2019)		---	129.83	31	Inhibition up 50% to 187 μg/mL
8	Melo et al. (2020)	*Botrytis cinerea* *Rhizopus stolonifer*	Strawberry	331	34	Inhibition <50% in fruit infected Inhibition >60% in fruit infected Inhibition <50% in fruit infected
9	López-Meneses et al. (2018)	*Aspergillus parasiticus*	Corn grain	361.9	43.8	Lower inhibition
10	Mondéjar-López et al. (2022)	*Aspergillus niger* *Aspergillus versicolor* *Fusarium oxysporum*	Wheat Oat Barley	172	49.8	MIC: 1.11 μg/mL MIC: >3.33 μg/mL MIC: 3.33 μg/mL On spore germinated
11	Abdel-Aliem et al. (2019)	*Aspergillus niger* *Aspergillus terreus* *Baeuvaria bassiana* *Fusarium oxysporum* *Fusarium graminearum*	Nut	180	---	Mycelium Inhibition >60% 800 ppm inhibits Zearalenone production
12	Alotaibi et al. (2019)	*Aspergillus flavus* *Aspergillus ochraceus* *Fusarium moniliforme*	*Phoenix dactylifera*	35–65	---	Inhibition of growth fungi evaluated
13	Hesami et al. (2021)	*Botrytis cinerea*	Strawberries	187	39	lowest inhibition against fruit decay to 20/μg mL
14	Mohammadi et al. (2015)			96.93	53	1500 ppm for inhibition up 50%
15	OH et al. (2019)	*Colletotrichum gelosporidies,* *Phytophthora capsica* *Sclerotinia sclerotiorum* *Fusarium oxysporum* *Gibberella fujikuori*	Tomato	~100–1000	---	Antifungal activity
16	Divya et al. (2018) Divya et al. (2017)	*Fusarium oxysporum* *Rhizoctonia solani* *Colletotrichum acutatum* *Phytophthora infestans*	Tomato Chilly Brinjal	20–70	---	Inhibited Mycelial radial growth: 63.88% at 40 mg/mL 84.72% at 50 mg/mL 76.72% at 50 mg/mL 32.16% at 50 mg/mL
17	El-Morsy et al. (2023)	*Fusarium equiseti*	Tomato	60	90.7	Inhibition rate for isolates: 40.39–66.0%
18	Kheiri et al. (2016)	*Fusarium graminearum*	Wheat	180.9	45.6	85% inhibition to 5000 ppm
19	Kheiri et al. (2017)					
20	Karamchandani et al. (2022)	*Fusarium moniliforme*	----	256 144	24.5 46.5	0.20% for inhibition fungal growth, up 80%
21	Muzzalupo et al. (2020)	*Fusarium proliferatum*	*Allium sativa*	260	25	Fungal inhibition up to 48.71%

#	Reference	Fungal	Crop	Characteristic nanoparticle Size (nm)	Characteristic nanoparticle Potential Z (mV)	Major findings for this review
22	Chouhan et al. (2022)	*Fusarium solani*	Wheat	21–124	---	65.50% of radial growth inhibition and 89% inhibition of spore germination to 40 μg/mL
23	Dananjaya et al. (2017)	*Fusarium oxysporum*	---	275	36	MIC: 400 μg/mL
24	Boruah and Dutta (2021)	*Sclerotium rolfsii* *Rhizoctonia solani*	---	310–342	-15.36	Chitosan from fungal chitin Maximum Radial growth inhibition: *Fusarium oxysporum*, 60.14% *Sclerotium rolfsii*, 45.03% *Rhizoctonia solani*, 63.2%
25	Hoang et al. (2022)	*Lasiodiplodia pseudotheobromae* *Alternaria alternate* *Penicillium digitatum*	Citrus	50–250	98.7	200 ppm exhibited the highest activity in totally inhibiting
26	Salem et al. (2022)	*Penicillium digitatum*	Citrus fruit	22.18–159.73	38.8	MFC for isolates 32.5–35 mg/mL
27	Xing et al. (2021)	*Penicillium steckii* *Aspergillus oryzae*	---	---	---	MIC: 5 mg/mL MFC: >5 mg/mL MIC: >5 mg/mL MFC: >5 mg/mL
28	Manikandan and Sathiyabama (2016)	*Pyricularia grisea*	Rice	83.32	-28	Not show direct inhibitory activity against fungi
29	Pham et al. (2019)	*Pyricularia oryzae*	Rice	25–30	-3	Lowest antifungal activity
30	Divya et al. (2020)	*Rhizoctonia solani*	*Oryza sativa L*	---	---	1000 μg/mL uppress 90% disease in detached leaf assay

---: not applicable or not reported. MFC: Minimal fungicide concentration MIC: Minimal inhibitory concentration.

Table 4. List of research studies (from 2013 to 2023) that evaluate Chitosan-TPP nanoparticles as carriers or composites of other molecules or substances against phytopathogenic fungi.

#	Reference	Fungal	Crop	Molecules or substances added to matrix nanoparticles	Characteristic nanoparticle Size (nm)	Characteristic nanoparticle Potential Z (mV)	Major findings for this review
1	Izadi et al. (2021)	*Alternaria alternata*	Tomato	*Carum copticum* EO	190.6	+29.4	Antifungal activity
2	Saharan et al. (2013)	*Macrophomina phaseolina* *Rhizoctonia solani*	---	Copper Saponins	180–487 200–990	+88 +31	High inhibition fungi
3	Saharan et al. (2015)	*Alternaria Solani* *Fusarium oxysporum*	Tomato	Copper	374.3	+22.6 mV	0.12% caused 70.5 and 73.5% inhibition of mycelia growth and 61.5 and 83.0% inhibition of spore germination in *Alternaria solani* and *Fusarium oxysporum*, respectively.
4	Karami-Osboo et al. (2023)	*Aspergillus flavus*	Pistachio nut	*Zataria multiflora* (Boiss) EO	293 ± 17	+16.8	inhibiting aflatoxin B1 production
5	Mumtaz et al. (2022)		----	Voriconazole	NA	NA	Antifungal activity
6	Singh et al. (2020a)		---	*Bunium persicum* (Boiss) EO	80–300	+33.8	Inhibition of 100% growth and aflatoxin B1 production to 0.8 μg/ml
7	Tiwari et al. (2022)		---	*Cinnamomum glaucescens* EO	45.8–104.8	---	MIC = 0.9 μL/mL aflatoxin inhibition to 0.8 μL/mL
8	Dwivedy et al. (2018)		*Pistacia vera*	*Illicium verum* EO	<200	---	Inhibiting aflatoxin B1 at 0.2 μL/mL
9	Das et al. (2021)		----	*Pimpinella anisum* EO	21–38	---	MIC: 0.08 μL/mL and inhibition antiaflaxotinB1
		Curvularia lunata *Alternaria humicola* *Alternaria alternata*					Nanoencapsulation preserved the antifungal properties for a longer time
10	Elshaer et al. (2022)	*Aspergillus niger*	---	Thompson Seedless *Vitis vinifera* juice extract Clotrimazole Thompson Seedless *Vitis vinifera* juice extract/Clotrimazole	59–124 67–75 50–89	--- --- +31	MIC:128 μg/mL MFC: 256 μg/mL MIC:32 μg/mL MFC: 64 μg/mL MIC:2 μg/mL MFC: 2 μg/mL

#	Reference	Fungal	Crop	Molecules or substances added to matrix nanoparticles	Characteristic nanoparticle		Major findings for this review
					Size (nm)	Potential Z (mV)	
11	Hasheminejad et al. (2019)		---	Clove EO	268	+22	Inhibition mycelial
12	El-Aziz et al. (2018)	*Aspergillus niger*	---	Mentha longifolia extract	157	≈+36	Antifungal activity
13	Mondéjar-López et al. (2022)	*Aspergillus versicolor* *Fusarium oxysporum*	Wheat Oat Barley	Garlic EO	172–352	+19–32	MIC: 0.37 μg/mL MIC: 3.33 μg/mL MIC: 1.11 μg/mL On spore germination
14	Nasiri-Jahrodi et al. (2022)	*Aspergillus fumigatus*	---	Eugenol	300–330	---	MIC: 300 μg/mL MFC: 600 μg/mL increase the expression of CYP51 gen
15	López-Meneses et al. (2018)	*Aspergillus parasiticus*	Corn grain	*Schinus molle L.* EO	516.9	+40.2	500 μg/mL inhibited up to 59% the aflatoxin production
16	Mohammadi et al. (2015)	*Botrytis cinerea*	Strawberry	*Zataria multiflora EO*	124.67–174.03	+46.6–67.8	750 ppm for inhibition 100%
17	Youssef et at. (2019)		Table grapes	Silica	48	---	100% inhibition to 10000 μg/mL
18	Hesami et al. (2021)		Strawberry	*Pistacia atlantica* EO	215.3–632.5	+10.46–34.11	Hight inhibition against fruit decay to 20 μg/mL
19	Wu et al. (2023)	*Colletotrichum gloeosporioides*	Strawberry	O-carboxymethyl chitosan/ tebuconazole	NA	NA	Antifungal activity
20	Chouhan et al. (2022)	*Fusarium solani*	Wheat	Niquel	300–400		100% of inhibition on spore germination and radial growth to 40 μg/mL
21	Dananjaya et al. (2017)	*Fusarium oxysporum*	---	Silver	373 ± 28	+47.5	MIC: 100 μg/mL
22	Kumar et al. (2022a)	*Fusarium pallidoroseum*	---	Mancozeb	292.4–443.9	+14.8–17.8	Antifungal activity
23	Muzzalupo et al. (2020)	*Fusarium proliferatum*	*Allium sativa*	*In vitro* Olive Leaf Extracts	254.6	16.9	Inhibition fungal up to 67.41%
24	Salem et al. (2022)	*Penicillium digitatum*	Citrus fruit	*Punica granatum* peel extract- selenite	24.58–164.71	+ 31.7	MFC for isolates 22.5–27.5 mg/mL
25	Pham et al. (2019)	*Pyricularia oryzae*	Rice	Protocatechuic acid	30–35	+11	Stronger anti-fungal properties at 5000 ppm
26	Sathiyabama and Muthukumar (2020)	*Pyricularia grisea*	Rice	*guar gum*	NA	NA	Activity against blight disease of rice
27	Jose et al. (2022)	*Pythium aphanidermatum*	---	clove oil	NA	NA	Antifungal activity
28	Sathiyabama et al. (2022)	*Rhizoctonia bataticola*	Chickpea	Thiamine	NA	NA	Antifungal activity
29	Mazzotta et al. (2022)	*Verticillium dahliae*	Tomato	Olive leaves extracts	331.26	21.1	MIC: 0.14 mg/mL

---: not applicable or not reported. NA: Full text is unavailable, only by subscription or buy article. EO: Essential oil. MFC: Minimal concentration fungicide.

natives to TPP that do not introduce compounds to the chitosan polymer matrix. Alternatively, safe compounds whose effects on the environment and non-target biological systems have been fully tested can be used. More research is required to determine the biological activity of chitosan-TPP and TPP.

Chitosan-only nanoparticles (nanochitosan)

This review exclusively focuses on nanoparticles made up of chitosan, but only twenty-six articles have studied nanoparticles without reporting the use of TPP in a composite matrix. The compounds mixed with chitosan are copper (Hassan et al. 2022; Dorjee et al. 2023), gold (Lipșa et al. 2020; Lipșa et al. 2021), nickel (Parthasarathy et al. 2023), silver (Matei et al. 2018; Gordienko et al. 2019), zinc (Alharbi et al. 2022), pinene (Hernández-López et al. 2020), proteins (Sathiyabama and Parthasarathy 2016; Hernández-Téllez et al. 2017), sodium sulfate (in place of TPP; Hashim et al. 2019), propolis (Cortés-Higareda et al. 2019), oil (Wardana et al. 2023), essentials oils (Luque-Alcaraz et al. 2016; Chávez-Magdaleno et al. 2018; Kalagatur et al. 2018; Yadav et al. 2019; Yilmaz et al. 2019; Kumar et al. 2020, 2022b; Singh et al. 2020b; Das et al. 2022), and vegetable extracts (Ali et al. 2022; El-Naggar et al. 2022; Istúriz-Zapata et al. 2022).

Only a few articles in this research have evaluated nanochitosan, which refers to nanoparticles made of chitosan-only. Some of these studies used nanochitosan as a control to compare the particle size of mixtures of chitosan and other compounds without evaluating the antifungal activity of nanochitosan itself (Kumar et al. 2019;

Singh et al. 2020b). Abdelraouf et al. (2023) used nanochitosan with a size range of 80–100 nm as a control in their experiment. They found that reduced the percentage of *Fusarium* wilt infection in tomato plants without affecting the growth of plants. In addition, Abdel-Rahman et al. (2021) reported that nanochitosan with a size of less than 100 nm and at concentrations of 0.2 and 0.4 g/L, inhibited the growth of *Penicillium expansum*, which is a pathogen that affects apples. Istúriz-Zapata et al. (2022) found that using nanochitosan (5 nm) up to a dosage of 100 µL/mL resulted in no growth of fungi *in vitro*, including *Colletotrichum asianum*, *Fusarium solani*, *Lasiodiplodia theobromae*, *Neofusicoccum oculatum*, *Pestalotiopsis mangiferae*, and *Talaromyces variabilis*. Chávez-Magdaleno et al. (2018) reported that nanochitosan had preventive activity against *Colletotrichum gloeosporioides* in avocados, while Wardana et al. (2023) discovered that (43.77–70.61 nm) exhibited antifungal activity against *Rhizopus stolonifer*. Moreover, in a study conducted by Cortés-Higareda et al. (2019), it was found that nanochitosan (3 nm) showed a minor inhibition of up to 25% on spore germination and mycelial growth in some fungi such as *Aspergillus flavus*. On the other hand, some reports have shown less or non-activity of nanochitosan against fungal pathogens. Luque-Alcaraz et al. (2016) discovered that nanochitosan (20–100 nm) did not significantly reduce the number of viable spores of *Aspergillus parasiticus in vitro*. This data suggests that the fungi may be lowly susceptible to nanochitosan. The above-described highlights the need to conduct more research to fully understand the benefits of nanochitosan in the combat against phytopathogenic fungi. Although nanoparticles have great potential to improve human life, handling and managing them correctly is important to prevent any negative effects on biological systems, including nanotoxicology.

Conclusions

This review delved into the characteristics of chitosan nanoparticles, both with and without TPP. However, only a limited number of studies investigated chitosan-only nanoparticles. Thus, there is a critical need for further research on nanochitosan to ensure their safe and effective use in biological systems, highlighting the significance of proper handling and precautionary measures.

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Competing interests

The author has declared that no competing interests exist.

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Supplementary material

Supplementary material 1

Research results from various databases (zip. archive)

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