



Vicia faba Fungal diseases: Could nanostructure drug delivery systems be a therapy?

Mohammed N. A. Hasaneen · Sara H. Helal ·
Mustafa M. El-Zayat · Heba M. M. Abdel-Aziz 

Received: 24 September 2024 / Accepted: 6 October 2025 / Published online: 7 November 2025
© The Author(s) 2025

Abstract In current applied research, innovative drug delivery systems have emerged as a strategy for managing plant diseases. The current study demonstrated the usefulness of three nano-drug delivery techniques for suppressing two fungal pathogens: *Botrytis fabae* and *Alternaria alternata*, which cause chocolate spot and minor disease leaf spot in *Vicia faba* plants. This work investigated the delivery of chitosan nanoparticles, carbon nanotubes, and solid lipid nanoparticles loaded with nystatin and fluconazole antifungals for infected *Vicia faba* plants through foliar uptake. All different nanoparticles loaded with either nystatin or fluconazole were easily applied to leaf surfaces and enter the stomata via gas uptake, avoiding direct interaction with soil systems. Transmission electron microscopy was used to evaluate nano-drug absorption, translocation, and biosafety in *Vicia faba* plants. The results obtained revealed that all different nanoparticles were taken up and

transported through phloem tissues, in particular, sieve tubes of either healthy, infected or recovered *Vicia faba* plants. On the other hand, growth and yield developmental parameters in the present study including plant height, number of pods per plants, number of seeds per pod, crop yield per plant, and crop index of healthy and recovered *Vicia faba* plants showed, in general, significant increases. The results show the possibility of these formulations to protect plants from the disease with a sequence of: solid lipid nanoparticles-loaded with fluconazole > chitosan nanoparticles loaded with fluconazole > carbon nanotubes loaded with fluconazole. The results indicate the possibility of these formulations to protect plants from the diseases with a sequence of solid lipid nanoparticles > chitosan nanoparticles > carbon nanotubes. Thus, it is suggested that solid lipid nanoparticles loaded with antifungals would be of use for the control of fungal diseases in crops such like *Vicia faba*.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10658-025-03145-7>.

M. N. A. Hasaneen · S. H. Helal ·
H. M. M. Abdel-Aziz (✉)
Botany Department, Faculty of Science, Mansoura
University, Mansoura, Egypt
e-mail: hebammabdelaziz@mans.edu.eg

M. M. El-Zayat
Department of Biology, Faculty of Science, New
Mansoura University, New Mansoura City, Egypt

Keywords Biosafety · Carbon nanotubes · Chitosan nanoparticles · Chocolate spot · Fluconazole · Growth and yield parameters · Leaf spot · Nano-drug delivery · Nystatin · Solid lipid nanoparticles · TEM · *Vicia faba* · Uptake and translocation

Introduction

Plant diseases reduce agricultural productivity. Using pesticides is the most popular form of protection

(Ramezani et al., 2019). The risks to the environment posed by overuse of pesticides has been discussed recently. Therefore, agricultural researchers keep looking for alternative ways to combat pests with biological control agents that can eradicate infections without negative impacts on the environment (Ade-tunji et al., 2017; Iavioli et al., 2017). A new class of nano-particles has emerged as a result of recent advances in nanoscale engineering. This technology uses biomimicry to better blend adjuvant and antigen (Rosenthal et al., 2014).

Antifungal drugs could be transported using nano-particles, which would reduce their toxicity and better target their effects. Lipid formulations first appeared in the 1990s, which marked the beginning of the use of nanoparticles for antifungal therapy. Various antifungal drug delivery techniques have been reported, including polymeric nanoparticles, solid lipid and nanostructure lipid carriers, liposomes, and others. Each of these delivery methods has benefits and drawbacks. The primary benefits are the improved antifungal characteristics, including absorption, decreased toxicity, and delivery to target tissue, (Vol-tan et al., 2016).

The faba bean, a member of the Fabaceae family that is indigenous to North and Southwest Africa, is one of Egypt's most significant economic winter crops (Ahmed, 2017; Mahmoud, 1996). Fungal diseases including chocolate spot (*Botrytis fabae*) and alternaria leaf spot (*Alternaria alternata*) damage faba bean plants and results in major reductions in yield (Mahmoud, 1996). In recent decades, bacteria and fungi have developed resistance to many traditional and modern synthetic drugs (WHO, 2012). In such instances, drug resistance mechanisms linked to reduced absorption, increased drug efflux from microbial cells, biofilm development, or intracellular biosynthesis can also be eliminated by nanoparticles (NPs) (Sardi et al., 2014). Ultimately, NPs overcome drug resistance with fewer negative effects on the plant by administering the antimicrobial drugs to the pathogen location (Pelgrift & Friedman, 2013).

The present study was carried out to evaluate the efficacy of chitosan nanoparticles (CSNPs), carbon nanotubes (CNTs) and solid lipid nanoparticles (SLNPs) either singly or loaded with nystatin (NYS) and fluconazole (FLZ) antifungals, as nano-drug delivery systems, as novel techniques for controlling *Botrytis fabae* and *Alternaria alternata* fungal

pathogens. In vivo studies deal with the effect of tested nano-drug delivery strategies on growth and productivity of *Vicia faba* plants, uptake and translocation and biosafety of nanomaterials used.

Materials and methods

Inoculum and inoculations

A spore suspension was injected in the leaflet at various locations. The leaflets were kept wet. There were four replicates of each concentration. Lesion size was measured from the third to the sixth day following incubation.

The effects of nanoparticles on infection with *Botrytis fabae* and *Alternaria alternata* under field conditions

Under field conditions, the effectiveness of nanoparticles (three types on nanoparticles: chitosan nanoparticles (CSNPs) strategy A, carbon nanotubes (CNTs) strategy B and solid lipid nanoparticles (SLNPs) strategy C), either alone or in combination with antifungal drugs, against *B. fabae* and *A. alternata* was observed. Faba bean seeds cv. Sakha 1 (susceptible cultivar to leaf spot disease) used in these field experiments were obtained from the Agricultural Research Center, Ministry of Agriculture, Mansoura, Egypt, and were grown in field. Based on the obtained data from the previous field and laboratory experiments (Abdel-Aziz et al., 2018), optimum effective concentrations of nanomaterials and/or minimum inhibitory concentration (MIC) of either nystatin or fluconazole were applied on the leaves of plants for 3 weeks before and after the disease outbreak. Growth and developmental parameters of *Vicia faba* yield were determined.

Uptake and translocation studies

Transmission electron microscopy (TEM) was used to examine the absorption and transport of nanoparticles in *Vicia faba* tissues.

Biosafety measurements

Vicia faba seeds that had been harvested were examined using a transmission electron microscope (TEM) to assess damage caused by the nano-particles (Abdel-Aziz et al., 2018).

Statistical analysis

The obtained data were analyzed by one-way analysis of variance (ANOVA), the mean values were compared using the Post Hoc L.S.D. (least significant difference) at 0.05 probability level.

Results

Characterization of chocolate spot disease and leaf spot disease

Chocolate spot symptoms were seen on leaves, stems, flowers, and pod tissues, as shown in figures S1-S2. Small reddish-brown circular lesions on leaves, stems, and flowers were the first signs of infection. The small dots on the stems and leaves grew larger, becoming grey in the middle and bordering on reddish-brown. In this investigation, one leaf will exhibit two stages: the non-aggressive stage, which is identified by small, distinct, circular reddish spots with darker borders, and the aggressive stage, which is characterized by the small spots combining and merging to produce irregular, bigger, dark-brown lesions that cover the entire leaf surface. The disease developed rapidly in favorable conditions, resulting in severe defoliation, flower drop, stem collapse, tissue necrosis, and ultimately plant death (figures S1-S2).

Careful examination of figures S3-S4 showed that lesions on the stem, pod, and other plant parts were originally brown, soaked in water, and shaped erratically to circular. These dark brown leaf regions resembled targets because they frequently possessed a zoned pattern of concentric brown rings with black edges. As the disease spread upward, the fungus showed that older leaves were typically infected first. Affected leaves went yellowish, became senescent, and either dried out and dropped or fell off. Most of the affected plants lost all of their leaves in the later stages of the illness, when the leaves blighted from the margin to the center.

Uptake and translocation of nanomaterials

In the current study, transmission electron microscopy (TEM) was used to examine plant leaves (46 days old) following the application of chitosan nanoparticles, carbon nanotubes, and solid lipid nanoparticles, either alone or in combination with the antifungal fluconazole or nystatin. This allowed us to determine whether nanomaterials were taken up through the leaves of broad bean plants during late vegetative growth and other developmental stages.

Careful examination of Figs. 1, 2 and 3 derived from TEM images of broad bean leaves (46-day-old) revealed the following main findings:

- a The vascular system of broad bean leaves treated with chitosan nanoparticles, carbon nanotubes, and solid lipid nanoparticles either singly or loaded with nystatin and fluconazole antifungal antibiotics showed total lack of nanomaterials either singly or loaded with these two antifungal antibiotics inside epidermal cells, cortical cells, spongy tissues, or palisade tissues (Figs. 1, 2 and 3).
- b Figs. 1, 2 and 3 demonstrated the foliar administration of the three nanoparticles to broad bean plants, either separately or in combination with nystatin and fluconazole. They also verified that the phloem tissues, particularly sieve tube cells, were responsible for the uptake and translocation of the nanoparticles.
- c It is important to note that the observed results regarding the uptake and translocation of nanomaterials by broad bean plants over the course of the experiment leads to the conclusion that the cells of the phloem sieve tubes served as the primary pathway for the uptake and translocation of nanomaterials, either alone or loaded with fluconazole and nystatin.

Changes in growth, yield and developmental parameters

All yield growth and developmental characteristics measured showed significantly different patterns under foliar treatment of either CSNPs, CNTs, or SLNPs alone or loaded with the antibiotics nystatin and fluconazole. Overall, the solid lipid nanoparticles

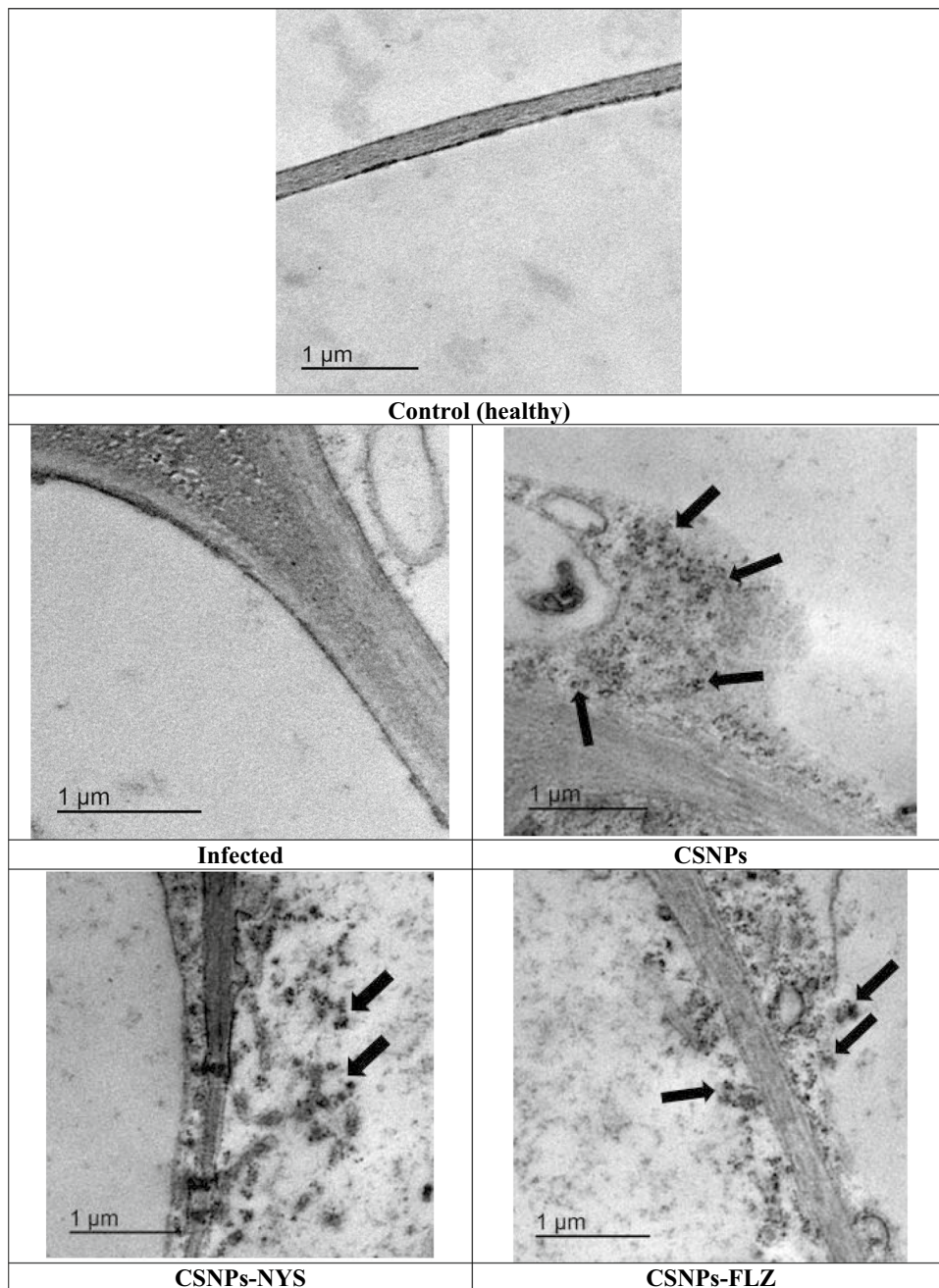


Fig. 1 TEM micrograph of phloem tissue of healthy, infected with *Botrytis fabae* and recovered 46-day-old *Vicia faba* leaves treated with chitosan nanoparticles (CSNPs) either singly or

loaded with nystatin (NYS) and fluconazole (FLZ) antifungal antibiotics. Arrows indicate presence of nanoparticles in the tissue

encapsulating fluconazole and nystatin showed the greatest increase in magnitude (Tables 1 and 2).

Additionally, it was found that, in comparison to values of diseased plants, the harvest index, crop index, and mobilization index values of broad

bean plants treated with nanomaterials, either alone or in combination with fluconazole and nystatin antifungal antibiotics, changed depending on the kind, manner, and dosage of the treatment. Thus, in general, as evident from Tables 1 and 2 the increase in harvest index was as follows: strategy C > strategy A > strategy B for *Botrytis fabae*. The percentage improvement in crop index was as follows: SLNPs + FLZ > SLNPs + NYS > CSNPs + FLZ > CSNPs + NYS > CNTs + FLZ > CNTs + NYS > diseased plants. Furthermore, the mobilization index as compared to the control was as follows: SLNPs + FLZ > SLNPs + NYS > CSNPs + FLZ > CSNPs + NYS > CNTs + FLZ > CNTs + NYS > diseased plants.

The growth and yield of the broad bean plants treated with nanomaterials, either alone or in combination with nystatin and fluconazole antifungal antibiotics, showed a significant improvement in terms for shoot length, number of pods per plant, pod weight per plant, number of seeds per plant, crop yield per plant, and seed yield per plant when compared to control diseased plants. As a nano-drug delivery technology, solid lipid nanoparticles loaded with nystatin or fluconazole showed the greatest improvement in these growth and developmental parameters (Tables 1 and 2).

Biosafety of yielded *Vicia faba* seeds

We determined the destiny of the investigated nanomaterials (CSNPs, CNTs, and SLNPs) either alone or loaded with nystatin and fluconazole after taking up by the plant tissue, especially in the phloem tissue (sieve tubes). This was accomplished by doing TEM examination on seeds that had undergone different treatments.

Careful examination of Fig. 4 revealed the following main points:

- a. A total absence of nanomaterials was seen in the tissues of seeds that were treated with various nanomaterials loaded with fluconazole and nystatin antifungal drugs.
- b. There was no discernible difference in the seed tissues of the plants treated with different nanomaterials. This suggests that there were no distinct nanomaterials present at all in the seed tissues.

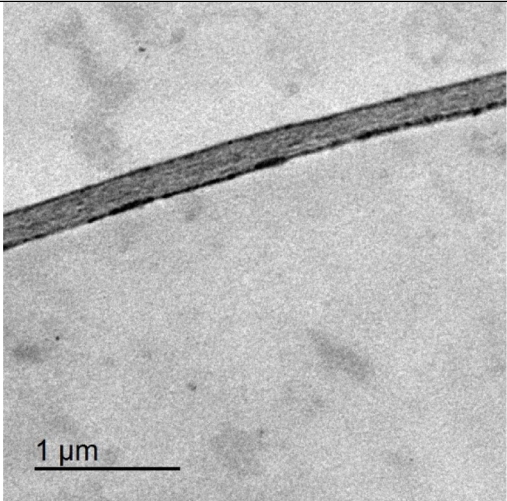
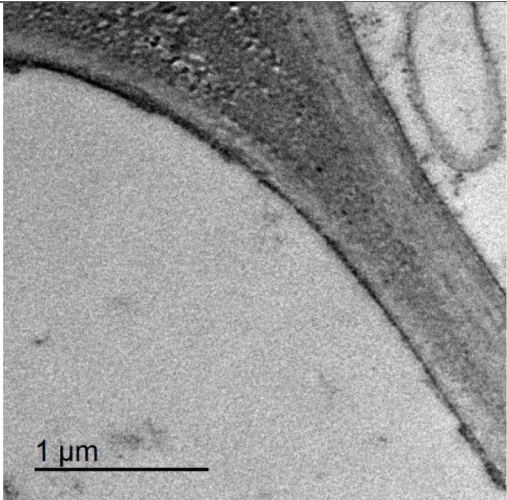
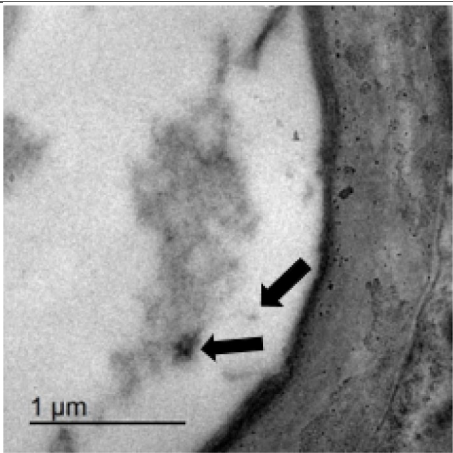
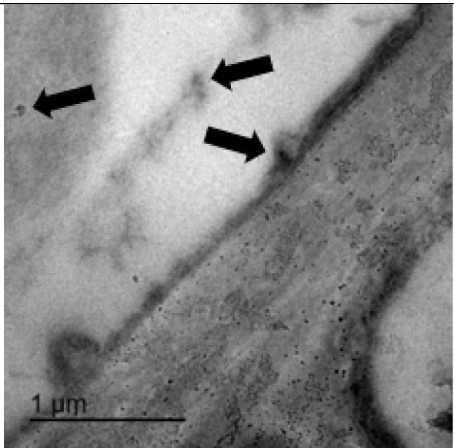
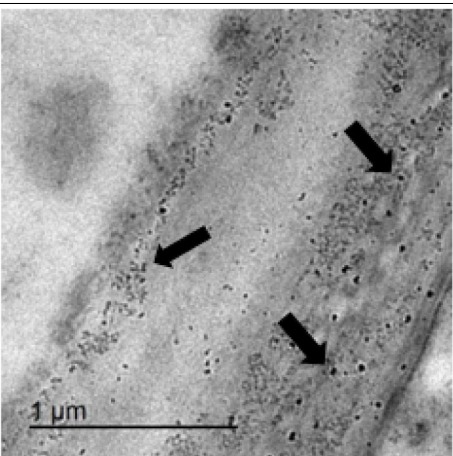
In summary, the present study compared three innovative and novel nano-drug delivery strategies to determine the percentage important and recovery from illness in broad bean plants affected by chocolate spot or leaf spot. The results showed that, generally, recovery from chocolate spot disease caused by the fungal pathogen *Botrytis fabae* was associated with the following treatment sequence: nano-drug delivery strategy C > nano-drug delivery strategy A > nano-drug delivery strategy B. However, the following order of treatments (nano-drug delivery strategy C > nano-drug delivery strategy A > nano-drug delivery strategy B) was generally demonstrated with respect to all growth and developmental yield parameters of the percentage improvement and recovered plants from illness with leaf spot disease caused by *Alternaria alternata* fungal pathogens, except for the results obtained for the mobilization index of broad bean yield.

Discussion

A. Uptake and translocation

The TEM images show that there are no nanomaterials in the epidermal cells, cuticle cells, spongy and palisade leaf tissues of healthy, diseased, and recovered broad bean plants. Nevertheless, there are nanomaterials in the vascular system of broad bean leaves that have been treated with the three different nanomaterials, either singly or loaded with nystatin and fluconazole. Careful examination of the images demonstrated that phloem tissues, specifically sieve tubes of broad bean plants, were responsible for the translocation of nanomaterials following foliar application of CSNPs, CNTs, or SLNPs either alone or in combination with nystatin and fluconazole. These findings demonstrate clearly the capacity of CSNPs, CNTs, or SLNPs to enter the broad bean phloem tissues and rapidly descend to the stem and root vascular tissues. The results of the experiment suggest that the primary route for the uptake and translocation of nanomaterials was through the phloem cells that line the tubes of leaves, stems, and ultimately descend to the roots.

In relation to the current findings, Lin et al. (Lin et al., 2009) and Hasaneen et al. (Hasaneen et al., 2016) demonstrated that capillary forces or osmotic

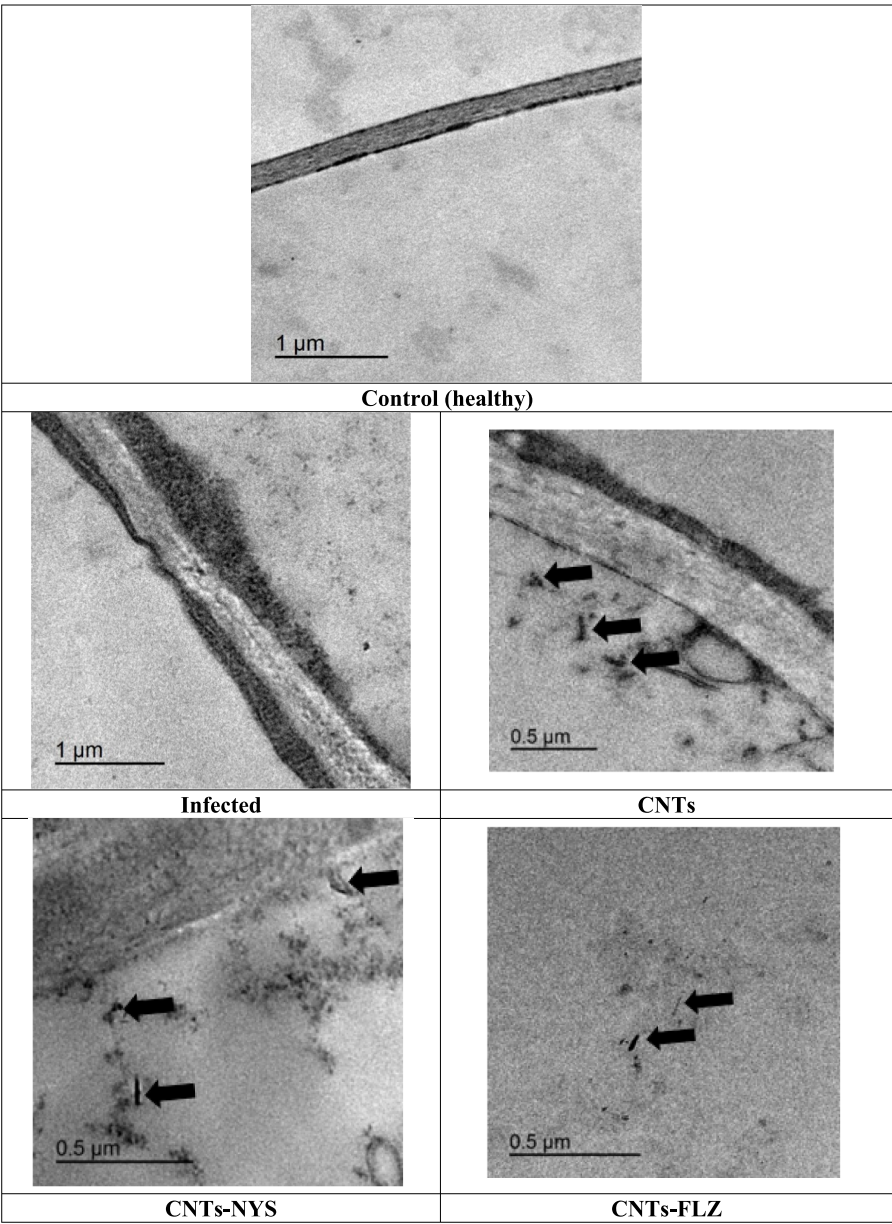
 Control (healthy)	
 Infected	 SLNPs
 SLNPs-NYS	 SLNPs-FLZ

◀**Fig. 2** TEM micrograph of phloem tissue of healthy, infected with *Botrytis fabae* and recovered 46-day-old *Vicia faba* leaves treated with solid lipid nanoparticles (SLNPs) either singly or loaded with nystatin (NYS) and fluconazole (FLZ) antifungal antibiotics. Arrows indicate presence of nanoparticles in the tissue

pressure can affect the diffusion of foliar sprayed nanomaterials when they pass cell wall pores in the area between the cell wall and plasma membrane. Nanoparticles can infiltrate epidermal and cortical cells via this pathway and eventually reach the

endodermis. But because the Casparian strip is waxy, aggregates build up in the endodermis. For nanoparticles to effectively translocate to the shoot, they must integrate into the symplastic pathway and penetrate the circulatory system (Larue et al., 2012). Nanoparticles can be transported via the strictly controlled symplastic pathway. The mechanisms for passive absorption were reinforced by increased production of aquaporin proteins and upregulation of water channel genes (Khodakovskaya et al., 2012).

Fig. 3 TEM micrograph of phloem tissue of healthy, infected with *Alternaria alternata* and recovered 46-day-old *Vicia faba* leaves treated with carbon nanotubes (CNTs) either singly or loaded with nystatin (NYS) and fluconazole (FLZ) antifungal antibiotics. Arrows indicate presence of nanoparticles in the tissue



b. Changes in yield growth and developmental parameters

Cell growth and developmental yield parameters were significantly increased in the current study. When comparing healthy, infected, and recovered *Vicia faba* plants to control plants, different changes were seen in the harvest index, crop index, and mobilization index. It is of interest to mention that nano-drug delivery strategies A, B and C, showed significant recovery from diseases in the case of crop index parameter of recovered *Vicia faba* plants.

Compared to the control, the nanoparticles containing antifungals showed improved efficacy against *Alternaria alternata* and *Botrytis fabae* (Ahmed, 2017; Helal et al., 2022). The current findings corroborate those of Kasproicz et al. (Kasproicz et al., 2010), who showed that certain plant diseases have been prevented by using silver nanoparticles. Additionally, Kasproicz et al. (Kasproicz et al., 2010) suggested that the development of disease is inhibited when nanoparticles come into direct contact with germ tubes or fungal spores. It is possible to draw the conclusion that nanomaterials loaded with antifungals,

Table 1 Effect of foliar application of different nanomaterials treatments either singly or loaded with nystatin and fluconazole on yield developmental parameters of faba bean plants grown in clay-sandy soil (before and after infection with *Botrytis*

fabae). In each case the % recovery from the infected plant is also shown. Each value is a mean of five replicates. *The values listed are significantly different from control at $p \geq 0.05$

Parameter Treatment	Plant height (cm plant ⁻¹)	% Recov	No. of pods/plant	% Recov	No. of seeds/pod	% Recov	Crop yield /plant (g plant ⁻¹)	% Recov	Crop index	% Recov
Control	61.11	—	4.00	—	3.00	—	6.59	—	0.37	—
Healthy Plant										
CNTs	60.32*	—	4.00	—	3.00	—	6.37*	—	0.33	—
CSNPs	66.71*	—	5.00*	—	3.00	—	11.30*	—	0.52*	—
SLNPs	64.12*	—	4.00	—	3.00	—	7.49*	—	0.44	—
Infected Plant with <i>Botrytis fabae</i>										
Infected plant	51.33*	—	3.00*	—	2.00*	—	2.96*	—	0.13*	—
NYS	63.65*	24.00	4.00	33.33	3.00	50.00	8.03*	171.28	0.41	215.38
FLZ	67.73*	31.95	4.00	33.33	3.00	50.00	9.00*	204.05	0.43	230.77
Strategy A										
A1: CSNPs	54.70*	6.57	3.00*	0.00	2.00*	0.00	4.73*	59.80	0.24*	84.62
A2: CSNPs-NYS	65.73*	28.05	5.00*	66.67	3.00	50.00	10.93*	269.26	0.54*	315.38
A3: CSNPs-FLZ	64.72*	26.09	5.00*	66.67	3.00	50.00	10.85*	266.55	0.55*	323.08
Strategy B										
B1: CNTs	51.78*	0.88	3.00*	0.00	2.00*	0.00	3.27*	10.47	0.16*	23.08
B2: CNTs-NYS	60.41*	17.69	4.00	33.33	3.00	50.00	7.15*	141.55	0.45	246.15
B3: CNTs-FLZ	61.88*	20.55	4.00	33.33	3.00	50.00	6.57	121.96	0.37	184.62
Strategy C										
C1: SLNPs	54.55*	6.27	3.00*	0.00	2.00*	0.00	3.25*	9.80	0.21*	61.54
C2: SLNPs-NYS	70.83*	37.99	5.00*	66.67	3.00	50.00	11.29*	281.42	0.58*	346.15
C3: SLNPs-FLZ	68.59*	33.63	5.00*	66.67	3.00	50.00	13.39*	352.36	0.60*	361.54

might be utilized to prevent harmful infections and manage faba bean leaf spot and chocolate spot. These types of nanomaterials might be less hazardous to human and the environment. The results of this study highlight the expanded use of nanomaterials, either alone or in combination with antifungal antibiotics for the control and management of *Alternaria alternata* and *Botrytis fabae* (Helal et al., 2022).

c. Biosafety of the yielded seeds

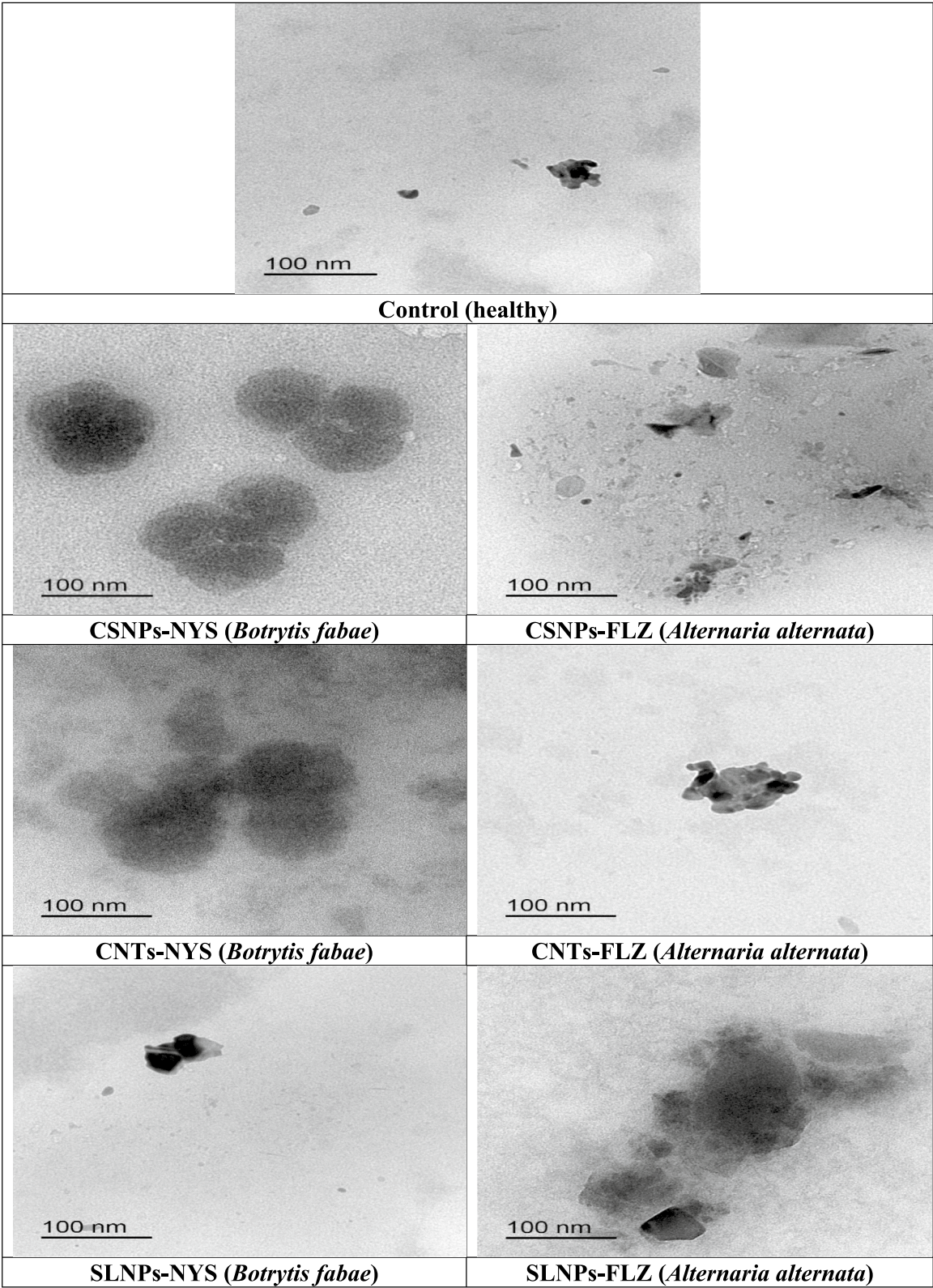
Plants can convey nanomaterials to ecosystems and humans through harvested organs, which can be hazardous to living things and have an impact on the

biodiversity and abundance of these environments. It is important to note that the current results (see Fig. 11) show that the *Vicia faba* seeds were completely free of any nanomaterials, suggesting that these nanomaterials were not stored inside the tissues of the seeds (see Fig. 4 distribution) (Murashov & Howard, 2007; Jo et al., 2009). It has been shown that nanoparticles could pass through the food chain which may cause threats to human health and safety (Deng et al., 2014; Marchiol et al., 2016; Rao, 2014). Therefore, comparing the antifungal activity of different kinds of nano systems should be done with caution. However, it is recommended to compare the antifungal effect of the nanoparticles with a potential control antifungal that has been authorized for field use.

Table 2 Effect of foliar application of different nanomaterials treatments either singly or loaded with nystatin and fluconazole on yield developmental parameters of faba bean plants grown in clay-sandy soil (before and after infection with *Alternaria*

alternata). In each case, the % recovery from the infected plant is also shown. Each value is a mean of five replicates. *The values listed are significantly different from control at $p \geq 0.05$

Parameter Treatment	Plant height (cm plant ⁻¹)	% Recov	No. of pods/ plant	% Recov	No. of seeds/ pod	% Recov	Crop yield /plant (g plant ⁻¹)	% Recov	Crop index	% Recov
Control	61.11	—	4.00	—	3.00	—	6.59	—	0.37	—
Healthy Plant										
CNTs	60.32*	—	4.00	—	3.00	—	6.37*	—	0.33	—
CSNPs	66.71*	—	5.00*	—	3.00	—	11.30*	—	0.52*	—
SLNPs	64.12*	—	4.00	—	3.00	—	7.49*	—	0.44	—
Infected Plant with <i>Alternaria alternata</i>										
Infected plant	50.46*	—	3.00*	—	2.00*	—	3.06*	—	0.13*	—
NYS	66.83*	32.44	4.00	33.33	3.00	50.00	8.42*	175.16	0.48*	269.23
FLZ	65.62*	30.04	4.00	33.33	3.00	50.00	8.66*	183.01	0.46*	253.85
Strategy A										
A1: CSNPs	53.61*	6.24	3.00*	0.00	2.00*	0.00	3.76*	22.88	0.21*	61.54
A2: CSNPs-NYS	63.32*	25.49	4.00	33.33	3.00	50.00	7.15*	133.66	0.43	230.77
A3: CSNPs-FLZ	64.21*	27.25	5.00*	66.67	3.00	50.00	10.12*	230.72	0.51*	292.31
Strategy B										
B1: CNTs	52.27*	3.59	3.00*	0.00	2.00*	0.00	3.08*	0.65	0.13*	0.00
B2: CNTs-NYS	61.73*	22.33	4.00	33.33	3.00	50.00	6.73*	119.93	0.43	230.77
B3: CNTs-FLZ	60.15*	19.20	5.00*	66.67	3.00	50.00	8.81*	187.91	0.49*	276.92
Strategy C										
C1: SLNPs	55.00*	9.00	3.00*	0.00	2.00*	0.00	3.47*	13.40	0.20*	53.85
C2: SLNPs-NYS	69.63*	37.99	5.00*	66.67	3.00	50.00	12.18*	298.04	0.54*	315.38
C3: SLNPs-FLZ	70.63*	39.97	5.00*	66.67	3.00	50.00	13.21*	331.70	0.63*	384.62



◀**Fig. 4** TEM micrographs of representative yielded seeds from *Vicia faba* plants treated with different tested nanomaterials loaded with nystatin and fluconazole as nano-drug delivery systems

Abbreviations *A. alternata*: *Alternaria alternata*; ANOVA: Analysis of variance; *B. fabae*: *Botrytis fabae*; CNTs: Carbon nanotubes; CNTs-FLZ: Carbon nanotubes loaded with fluconazole; CNTs-NYS: Carbon nanotubes loaded with nystatin; CSNPs: Chitosan nanoparticles; CSNPs-FLZ: Chitosan nanoparticles loaded with fluconazole; CSNPs-NYS: Chitosan nanoparticles loaded with nystatin; FLZ: Fluconazole; L.S.D.: Least significant difference.; MIC: Minimum inhibitory concentration; NPs: Nanoparticles; NYS: Nystatin; SLNPs: Solid lipid nanoparticles; SLNPs-FLZ: Solid lipid nanoparticles loaded with fluconazole; SLNPs-NYS: Solid lipid nanoparticles loaded with nystatin; TEM: Transmission electron microscopy

Acknowledgements Not applicable

Authors' contribution Conceptualization, M.N.A.H., and H.M.M.A.-A.; methodology, S.H.H. and H.M.M.A.-A.; software, S.H.H. and H.M.M.A.-A.; validation, M.M.E.; formal analysis, S.H.H. and H.M.M.A.-A.; investigation, S.H.H.; resources, M.N.A.H., and H.M.M.A.-A.; data curation, S.H.H. and H.M.M.A.-A.; writing—original draft preparation, S.H.H., H.M.M.A.-A. and M.N.A.H.; writing—review and editing, H.M.M.A.-A. and M.N.A.H.; visualization, M.M.E., M.N.A.H. and H.M.M.A.-A.; supervision, M.M.E., M.N.A.H. and H.M.M.A.-A.; project administration, M.M.E., M.N.A.H. and H.M.M.A.-A.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors declare that they had no funding for the present research.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable

Data availability All data generated or analyzed during this study are included in this article.

Competing interests The authors declare that they have no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abdel-Aziz, H. M. M., Hasaneen, M. N. A., & Omar, A. M. (2018). Effect of foliar application of nano chitosan NPK fertilizer on the chemical composition of wheat grains. *Egyptian Journal of Botany*, 58, 87–95.
- Adetunji, C., Oloke, J., Kumar, A., Swaranjit, S., & Akpor, B. (2017). Synergetic effect of rhamnolipid from *Pseudomonas aeruginosa* C1501 and phytotoxic metabolite from *Lasiodiplodia pseudotheobromae* C1136 on *Amaranthus hybridus* L. and *Echinochloa crus-galli* weeds. *Environmental Science and Pollution Research*, 24, 13700–13709.
- Ahmed, A. I. S. (2017). Chitosan and silver nanoparticles as control agents of some Faba bean spot diseases. *Journal of Plant Pathology and Microbiology*, 8, 421.
- Deng, Y., White, J. C., & Xing, B. (2014). Interactions between engineered nanomaterials and agricultural crops: Implications for food safety. *Journal of Zhejiang University. Science*, 15, 552–572.
- Helal, S. H., Hasaneen, M. N. A., El-Zayat, M. M. & Abdel-Aziz, H. M. M. (2022). *In vitro* efficacy of antifungal activities either singly or loaded on nanomaterials, as new and novel drug delivery systems on the growth of *Alternaria alternata* and *Botrytis fabae* fungal pathogens. *Mansoura Journal of Biology*, 59, 54–61.
- Hasaneen, M. N. A., Abdel-Aziz, H. M. M., & Omer, A. M. (2016). Effect of foliar application of engineered nanomaterials: Carbon nanotubes NPK and chitosan nanoparticles NPK fertilizer on the growth of French bean plant. *Biochemistry Biotechnology Research*, 4, 68–76.
- Iavioli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and Applied Pharmacology*, 329, 96–111.

- Jo, Y. K., Kim, B. H., & Jung, G. (2009). Antifungal activity of silver ions and nanoparticles on phytopathogenic fungi. *Plant Disease*, 93(10), 1037–1043. <https://doi.org/10.1094/PDIS-93-10-1037>
- Kasproicz, M. J., Koziol, M., & Gorczyca, A. (2010). The effect of silver nanoparticles on phytopathogenic spores of *Fusarium culmorum*. *Canadian Journal of Microbiology*, 56, 247–253.
- Khodakovskaya, M., de Silva, K., Dervishi, E., Biris, A. S., & Villagarcia, H. (2012). Carbon nanotubes induce growth enhancement of tobacco cells. *ACS Nano*, 6, 2128–2135.
- Larue, C., Pinault, M., & Czarny, B. (2012). Quantitative evaluation of multiwalled carbon nanotube uptake in wheat and rape seed. *Journal of Hazardous Materials*, 228, 155–163.
- Lin, S., Reppert, J., Hu, Q., Hunson, J. S., Reid, M. L., Ratnikova, T., Rap, A. M., Luo, H., & Ke, P. C. (2009). Uptake, translocation and transmission of carbon nanomaterials in rice plants. *Small (Weinheim an der Bergstrasse, Germany)*, 5, 1128–1132.
- Mahmoud, N. M. (1996). Studies on chocolate spot disease of broad bean and loss occurrence. *Ph.D. Thesis, Faculty of Agriculture, Minufiya University*. p. 133.
- Marchiol, L., Mattiello, A., Pošćic, F., Fellet, G., Zavalloni, C., Carlino, E., & Musetti, R. (2016). Changes in physiological and agronomical parameters of barley (*Hordeum vulgare*) exposed to cerium and titanium dioxide nanoparticles. *International Journal of Environmental Research and Public Health*, 13, 1–18.
- Murashov, V., & Howard, J. (2007). Biosafety, occupational health and nanotechnology. *Applied Biosafety*, 12, 158–167.
- Pelgrift, R. Y., & Friedman, A. J. (2013). Nanotechnology as a therapeutic tool to combat microbial resistance. *Advanced Drug Delivery Reviews*, 65, 1803–1815.
- Ramezani, M., Ramezani, F., & Gerami, M. (2019). Nanoparticles in pest incidences and plant disease control. In D. Panpatte, Y. Jhala (Eds.), *Nanotechnology for agriculture: Crop production & protection* (pp. 233–272). Springer.
- Rao, V. (2014). Systems approach to biosafety and risk assessment of engineered nanomaterials. *Applied Biosafety*, 19, 11–19.
- Rosenthal, J. A., Chen, L., Baker, J. L., Putnam, D., & DeLisa, M. P. (2014). Pathogen-like particles: Biomimetic vaccine carriers engineered at the nanoscale. *Current Opinion in Biotechnology*, 28, 51–58.
- Sardi, J. C. O., Pitangui, N. S., Rodríguez-A. G., Taylor, M. L., Fusco-Almeida, A. M. & Mendes-Giannini, M. J. S. (2014). Highlights in pathogenic fungal biofilms. *Revista Iberoamericana de Micología*, 31, 22–29.
- Voltan, A.R., Quindos, G., Alarcón, K.P.M., Fusco-Almeida, A.M., Mendes-Giannini, M.J.S. & Chorilli, M. (2016). Fungal diseases: could nanostructured drug delivery systems be a novel paradigm for therapy?. *International Journal of Nanomedicine* 11
- WHO. (2012). *Options for action*. WHO Publication.
- This research was performed using seeds of *Vicia faba* (cultivated crop) obtained from the Agricultural Research Center, Ministry of Agriculture, Mansoura, Egypt. In our work we comply with local, national and international guidelines. This work was not performed on wild or endangered plants. Our work complies with the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.