J. of Plant Protection and Pathology, Mansoura Univ., Vol. 16 (10):503 - 510, 2025

Journal of Plant Protection and Pathology

Journal homepage & Available online at: www.jppp.journals.ekb.eg

Efficacy of Silicon and Chitosan Nanoparticles as Eco-Friendly Agents Against *Aspergillus niger* Fruit Rot in Dates

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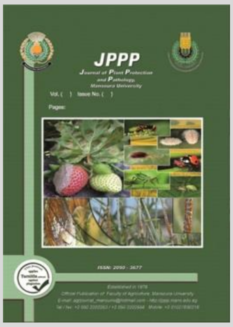

Article Information
Received 6 / 9 /2025
Accepted 15/ 10/2025

ABSTRACT

Postharvest diseases are one of the major constraints affecting the quality and marketability of date fruits. *Aspergillus niger* is one of the most damaging pathogens causing black rot. This study aimed to evaluate the antifungal effectiveness of chitosan nanoparticles (ChNPs) and silicon nanoparticles (SiO_2NPs) as eco-friendly alternatives to fungicides. The pathogen was isolated and identified morphologically and molecularly as *A. niger*. Transmission electron microscopy (TEM) and X-ray diffraction (XRD) confirmed the successful synthesis of ChNPs and SiO_2NPs with nanoscale characteristics. *In vitro* assays indicated significant inhibition of mycelial linear growth, with the highest suppression observed at 100 ppm of SiO_2NPs (96.30%) and ChNPs (92.59%). *In vivo* application on date fruits demonstrated that both nanoparticles reduced disease incidence and severity. At a concentration of 100 ppm, SiO_2NPs and ChNPs achieved the tiniest disease incidence (6.66% and 26.66%, respectively) after 10 days compared to the control. Further, treatments effectively maintained fruit weight and total soluble solids (TSS), indicating improvements in postharvest quality. The results indicate the potential of chitosan and silicon nanoparticles as sustainable and safe agents for controlling *A. niger*-induced fruit rot in dates, offering a promising alternative to fungicides.

Keywords: Postharvest, fruit rot, nanoparticles

INTRODUCTION

One of Egypt's most economically and nutritionally significant fruit crops, especially in the New Valley governorate, are date palm fruits (*Phoenix dactylifera* L.). Date fruit quality and marketability are severely hampered by postharvest diseases, which also threaten food security and cause large financial losses. Aspergillus fungus, especially *A. niger*, are among the most dangerous postharvest diseases. (Klich, 2007; Pitt & Hocking, 2009). *A. niger* is known to be a common postharvest fungal pathogen that damages date fruits, resulting in black mold disease that severely degrades their quality. *A. niger* infection causes tissue deterioration and a loss of marketability by weakening the fruit flesh and causing obvious fungal growth on the surface that appears greenish black. The high temperatures and humidity seen in date storage and transportation conditions are ideal for the growth of this fungus. Thus, it is essential to use efficient decontamination techniques to maintain the safety and quality of date fruit (Palou *et al*., 2016; Al-Mokadem *et al*., 2022). Due to health, environmental, and regulatory issues, the traditional use of synthetic fungicides to reduce postharvest rot has become more difficult. As a result, demand for secure, environmentally responsible, and efficient substitutes is rising. Because of its broad-spectrum antibacterial action and capacity to trigger defense responses in plant tissues, chitosan—a naturally occurring biopolymer produced from chitin Zhang et al. (2013) has demonstrated significant potential among these. (El Ghaouth *et al*., 1992; Rabea *et al*., 2003). Chitosan improves resistance to infection by interfering with fungal cell membranes, causing intracellular components to leak, and activating host defense enzymes such polyphenol oxidase (PPO) and peroxidase (POD) (Al-Mokadem et al., 2022). Simultaneously, silicon has become a useful component for improving plant resilience to biotic stress. Through silica deposition and the modification of defense-related pathways, silicon helps to fortify cell walls even though it is not thought to be necessary for plant growth (Epstein, 1999; Ma & Yamaji, 2006). Fawe et al. (1998) and Rodrigues et al. (2005), mentioned that the application of silicon inhibits the growth of fungi by causing the accumulation of phenolic compounds and activating important antioxidant enzymes. Silicon treatments have been shown to decrease disease incidence and increase fruit shelf life, including citrus and grapes, in postharvest systems (Moscoso-Ramírez & Palou, 2015; Garde-Cerdán, 2023). This study is to assess the antifungal efficacy of nano chitosan and nano silicon against *A. niger* on date palm fruits, given the importance of Aspergillus-induced postharvest degradation and the pressing need for safer management approaches.

MATERIALS AND METHODS

1- Sample collection and isolation causal pathogen

A pathogenic fungus was isolated from samples appeared softening of the fruit flesh visible fungal growth on the surface appearing as a greenish black. The samples were collected from different market in the Kharga Oasis, the New Valley Governorate, Egypt. According to Pitt and Hocking (1985). Small pieces from the margin of the lesion of samples were inoculated on prepared plates of Potato dextrose agar. The medium was supplemented with antibiotic (250 mg per liter) as a bacteriostatic agent (Smith and Dawson, 1944). The plates were inoculated at 28 ± 1°C for 5 days.

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DOI: 10.21608/jppp.2025.420175.1380

2- Molecular identification

The genomic DNA of *Aspergillus niger* was isolated at the Molecular Biology Research Unit, Assiut University using Patho-gene-spin DNA/RNA extraction kit (Intron Biotechnology Company, Korea). PCR reactions were amplified using the universal fungus internal transcribed spacer (ITS1) primer pair: ITS1 (5'- TCCGTAGGTGAA CCTGCGG - 3') (De Hoog and van den Ende, 1998) and ITS4 (5'- TCCTCCGCTTATTGATATGC - 3') (White et al., 1990). Amplified products were subjected to sequencing, SolGent PCR Purification Kit-Ultra (SolGent, Daejeon, South Korea). Database for BLAST search tools at NCBI (http://blast.ncbi.nlm.nih.gov/BLAST.cgi) was used to analyze the obtained sequence. Clustal W software (Thompson *et al*. 1994) was used for multiple sequence alignment of ITS sequence from other isolated sequences of *Aspergillus* sp. Phylogenetic tree was constructed using a neighbour-joining method by using MegAlign (DNA Star) software version 5.05.

3- Pathogenicity test

For the confirmation of *Aspergillus niger* damage dates fruit, a pathogenicity test was performed on five surface-sterilized date fruits. The fruits were inoculated by using an inoculation needle carrying mycelia of *A. niger* grown on PDA medium before 5 days and placed in autoclaved beakers for 10 days. Also, five fruits were inoculated with sterile PDA as a control. After the confirmation of pathogen establishment, the *A. niger* conidia were re-isolated from the lesions developed on dates. (Anjili *et al*., 2015; Palou *et al.,* 2016).

4- Preparation of Nanoparticles

Nano chitosan and nano silicon were prepared by Nanotechnology & Advanced Nano-Materials Laboratory (NANML)-Mycology & Disease Survey Research Dep. Agriculture Research Center (ARC).

5- Transmission Electron Microscope (TEM)

TEM images were performed on JEOL JEM-2100 high resolution transmission electron microscope at an accelerating voltage of 200 kV, respectively. (Haider *et al.,* 1998; Bhattarai *et al.,* 2019).

6- X-Ray Diffraction Analysis (XRD)

The structural characterization of the prepared silica (SiO_2) and chitosan nanoparticles was carried out using X-ray diffraction (XRD). The analysis was performed on a diffractometer equipped with Cu-Kα radiation (λ = 1.5406 Å), operated at 40 kV and 30 mA. Diffraction patterns were recorded over a 2θ range of 10° to 80° with a scan rate of 2°/min and a step size of 0.02°. (Dananjaya *et al*., 2017; El-Mohamedya *et al*., 2019)

7- Bioassay of Nano-Silicon and Nano-Chitosan on mycelial linear growth of *Aspergillus niger In Vitro*

Poison food technique was used to measure the antifungal activity (Pochanavanich and Suntornsuk, 2002). Different concentrations (25, 50 and 100 ppm) of Chitosan and Silicon nanoparticles in aqueous solution were used in antifungal activity test against *A. niger* PDA medium was prepared and poured in Petri dishes (90 mm), with above-mentioned percentages of various nanoparticles, separately. Mycelial bit from peripheral end of uniform size (diameter, 5.0 mm) was taken from 5 days old culture of *A. niger* and placed in the center of test Petri dishes. All the Petri dishes were incubated at 28 ± 1 °C for 5 days and the observation of radial mycelial growth was recorded when control Petri dish cover full growth (90 mm). All the treatments consisted of three replications. The inoculated plates were compared with control (without nanoparticles) to calculate the % inhibition rate of mycelia of the pathogen by using the formula described by (Abd-El-Khair, 2011) as follows:

Growth inhibition % = [(A–B)/A] x100

Where:

A= diameter of mycelial growth in control plates.

B= diameter of mycelial growth in treated plates.

8- In *vivo* assessment of Nano-Silicon and Nano-Chitosan against dates fruit rot.

Dates were surface-disinfected by immersion in 0.5% sodium hypochlorite for 2 min, then rinsed thoroughly with sterile distilled water. Fruits were soaked in three different concentrations 25, 50 and 100 ppm of each nano-chitosan and nano-silicon. Fruit without any treatment were used as control. Three replicates each containing five dates were used for each replicate. Inoculation of this fruit by using an inoculation needle carrying mycelia of *Aspergillus niger* previously were grown on PDA at 25°C for 5 days pri inoculation. Inoculated fruit were placed in humid chambers and incubated at 20°C for 10 days. Disease incidence, disease severity and weight loss were recorded every 3 days at all treatment on stored fruit (Saqib *et al*., 2020).

9- Total soluble solid (TSS) measurement

After the experiment was completed, the date fruit samples were subjected to TSS measurement using a digital refractometer 0-32 °Brix (Atago Co., Tokyo, Japan). (model: PR-32α, Palette digital refractometer, ATAGO, CO., LTD. Tokyo, Japan) which provided the ºBrix value with an accuracy of +/- 0.1%. The TSS content of date fruit samples was measured according to (Dadzie and Orchard 1997). Prepared the Juice of date fruit by thoroughly mixing 50 g of tissue pulp in 50 ml distilled water for 2 min and then passing it through a filter paper. Then one drop of filtrate was placed on the prism of the refractometer and recorded the ºBrix value. The recorded value was multiplied by '3' as the dilution facto.

10- Statically analysis:

The experimental data were statistically analyzed using single factor ANOVA. Post-hoc comparisons were carried out using revised Least Significant Difference (L.S.D. revised) on COSTAT statistical software version 6.303–CoHort Software as mentioned by Gomez and Gomez, 1984.

RESULTS AND DISCUSSION

Results

1- Sample collection and isolation causal pathogen

Samples of dates were obtained from various marketplaces in El-Kharga City, New Valley Governorate of Egypt. The first visible symptoms of the infected dates fruit were softening of the fruit flesh visible fungal growth on the surface appearing as a greenish black, which is a characteristic feature of *Aspergillus niger* infection Figure 1. These observations suggest that *A. niger* is strongly associated with the deterioration symptoms recorded on the date fruits. The mature *A. niger* colony was identified based on its macroscopic features. It initially appears white and rapidly turns black as conidia develops. The black coloration is due to the heavy production of dark pigmented conidia. Also, the microscopic examination of *A. niger* growth revealed that Hyphae were thick-walled, septate and branched. The conidiophore was wide with a long stipe, smooth-walled, and brown, the conidial head, globose, wider vesicle. Conidia varied in size, globose, brown, and rough-walled Fig. 2.

Fig. 1. Natural infection symptoms of date palm fruits during sample collection.

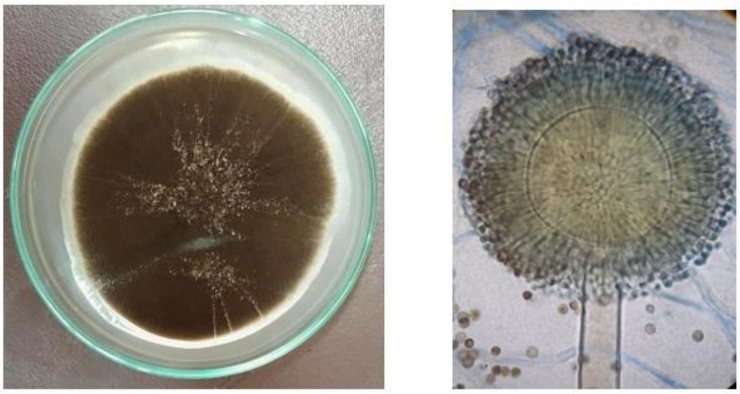

Fig. 2. Macroscopic and microscopic examination of *A. niger* isolated from Natural infection symptoms of date palm fruits.

2- Molecular identification

Aspergillus niger isolate was identified using molecular methods. Sequences were compared with those available in public GenBank databases, to confirm the morphological identification. Molecular analysis was conducted based on the internal transcribed spacer (ITS) region of rDNA sequences. As demonstrated in Fig. 3, Phylogenetic tree based on ITS sequences of rDNA of the fungal sample isolated in the present study (*Aspergillus niger* AUMC16164, arrowed) aligned with closely related strains accessed from the GenBank. This strain showed 100% identity and 98% -100% coverage with several strains of the same species.

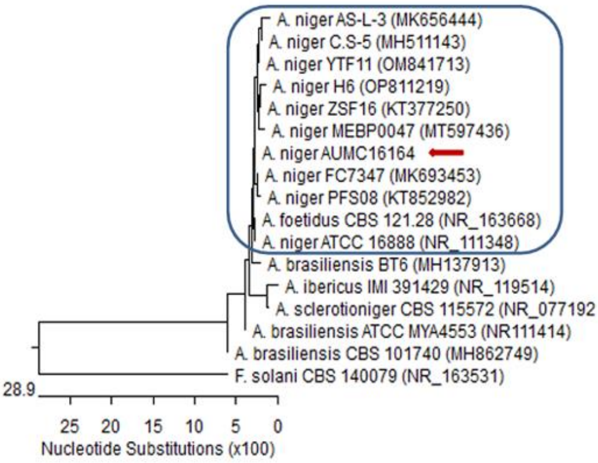

Fig. 3. Phylogenic tree of *Aspergillus niger AUMC16164* caused dates fruit rot. *Fusarium solani* represents the outgroup strain. *A.* = *Aspergillus*, *F.* = *Fusarium*

3- Pathogenicity test

The pathogenicity of the characteristic *Aspergillus niger* AUMC16164 was confirmed by inoculating fruit dates. All the inoculated fruit dates showed complete symptoms after 10 days of inoculation (Fig. 4). Initially, visible symptoms of the infected dates fruit were softening of the fruit flesh, then visible fungal growth on the surface, appearing as a greenish black. These symptoms are the same as those of the naturally infected fruit dates. The pathogen was re-isolated from the infected fruit dates, producing the same pathogen characteristic features.

Fig. 4. The symptoms on date fruit after 10 days of inoculation from pathogenicity.

4- Characterization of Nanoparticles:

As shown in Fig. 5 indicates the characterization of prepared SiO_2 nanoparticles, the transmission electron microscopy (TEM) image shows the morphology of the synthesized SiO_2NPs. The image was acquired at a direct magnification of 20,000× using an accelerating voltage of 100.0 kV. The Si NPs tend to form agglomerates. The average particle size is estimated to be in the range of 10–30 nm. The relatively uniform distribution and nanoscale features indicate successful synthesis of silicon nanoparticles. The XRD pattern of the synthesized SiO_2 nanoparticles exhibits a broad diffraction peak centered around $2\theta \approx 22°$, which is characteristic of amorphous silica.

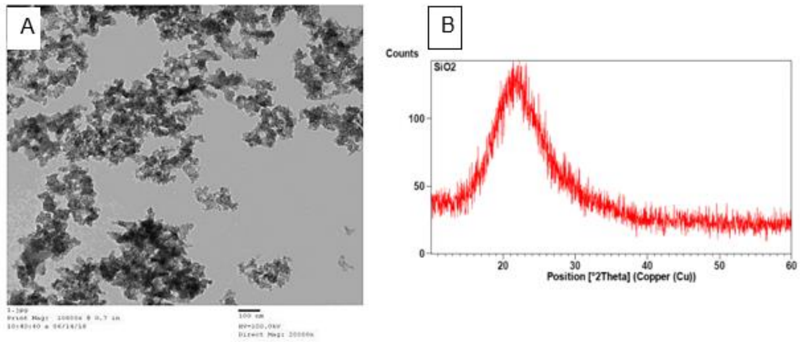

Fig. 5. Characterization of prepared SiO_2 nanoparticles. A= TEM image and B= XRD pattern

As shown in Fig. 6 indicates the characterization of prepared chitosan nanoparticles, the transmission electron microscopy (TEM) image shows the morphology and distribution of chitosan nanoparticles. The particles appear as spherical shapes, uniformly dispersed. The absence of significant agglomeration suggests good colloidal stability and effective synthesis. the X-ray diffraction (XRD) pattern of chitosan nanoparticles shows a broad diffraction peak centered around $2\theta \approx 20°$, which is characteristic of the semi-crystalline nature of chitosan.

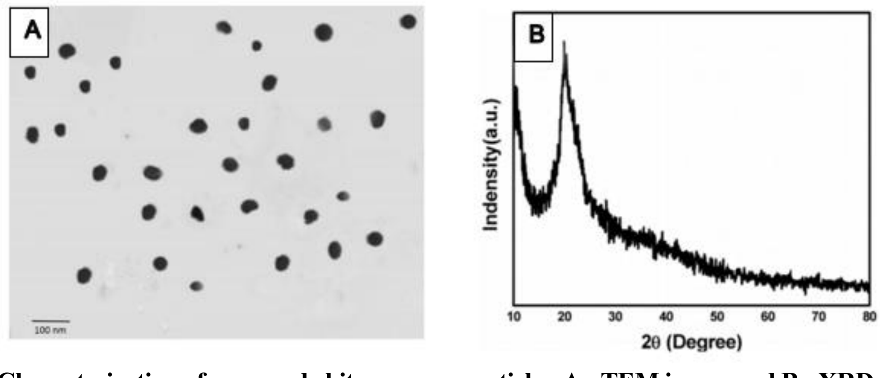

Fig. 6. Characterization of prepared chitosan nanoparticles. A= TEM image and B= XRD pattern

5- Bioassay of nanoparticles on mycelial linear growth of *Aspergillus niger In Vitro.*

Data in Fig.7 show that the inhibitory effect of chitosan and silicon nanoparticles at three concentrations of each one on the mycelial linear growth of *A. niger* was measured as a percentage of growth inhibition in vitro. All tested treatments exhibited significant inhibition compared with the control. The highest growth inhibition was observed with silicon and chitosan at 100 ppm concentration (96.30% and 92.59% respectively), followed by intermediate concentrations of chitosan and silicon at 50 ppm, were recorded 67.04% and 67.41% respectively. The lowest inhibition levels were obtained with the lowest concentrations, ChNPs at 25 ppm (34.44%) and SiO_2NPs at 25 ppm (35.19%). Fig. 8 illustrates that effect of nanoparticles treatments on mycelial linear growth of Aspergillus niger In Vitro. Chitosan and silicon nanoparticles at 100 ppm were the most effective in suppressing fungal growth.

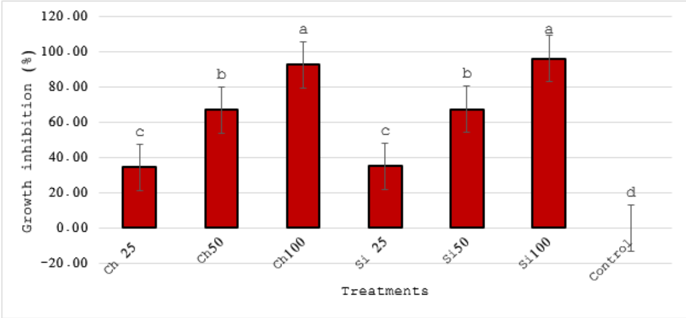

Fig. 7. Effect of treatments on mycelial linear growth of *Aspergillus niger In Vitro*
L.S.D. at 5%: 6.48. Columns with the same letters do not differ significantly according to LSD test (P ≤ 0.05).

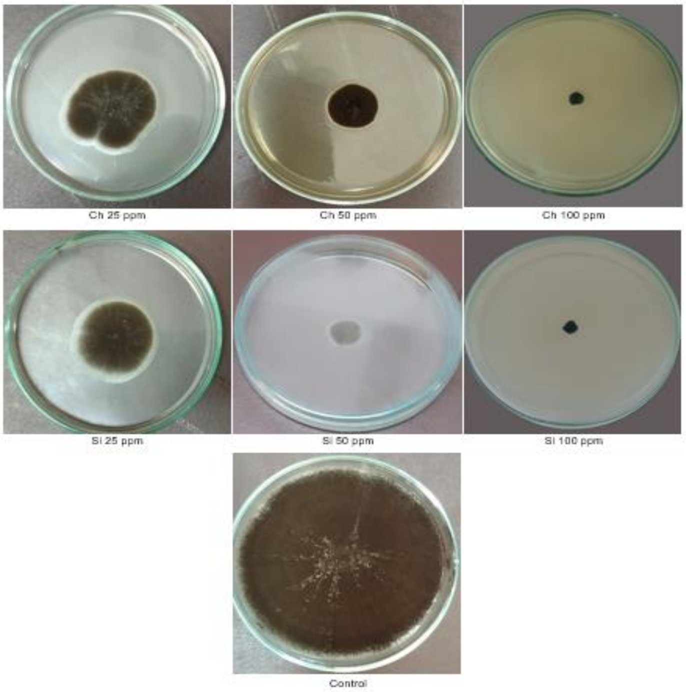

Fig. 8. *A. niger* growth inhibition *in vitro* by nanoparticles treatment.

6- *In vivo* assessment of Chitosan and Silicon Nanoparticles against date fruit rot.

A- Effect of Chitosan and Silicon Nanoparticles on the incidence of date fruit rot.

The results presented in Fig. 9 demonstrate that treatments with both chitosan and silicon nanoparticles significantly reduced disease incidence compared to the control, which consistently recorded 100% infection at all time intervals. For ChNPs, the treatment with ChNPs at 100 ppm concentration exhibited the highest efficacy, showing complete protection, preventing disease occurrence up to 3 days (0%) and the incidence rate gradually increased to 6.66% and 26.66% at 6 and 10 days, respectively.

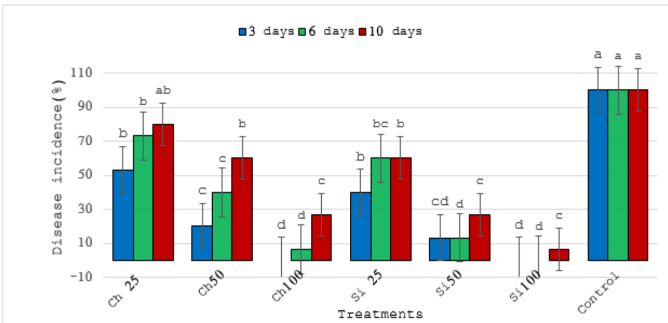

Fig. 9. Effect of treatments 3,6 and 10 days on the development of disease incidence (%)
L.S.D. at 5% for: 3 days= 18.33, 6days=22.93 and 10 days=22.93. Columns with the same letters do not differ significantly according to LSD test (P ≤ 0.05).

The moderate concentration of ChNPs at 50 ppm showed partial effectiveness, with disease incidence recorded at 20% after 3 days and 60% after 10 days, while the lowest concentration of ChNPs at 25 ppm had the weakest impact, where disease incidence was recorded at 80% after 10 days, approaching the control level. Similarly, SiO_2NPs treatments followed a comparable trend. The SiO_2NPs at 100 ppm concentration treatment achieved complete suppression of disease incidence up to 6 days (0%) and maintained a very low level (6.66%) at 10 days. The SiO_2NPs at 50 ppm concentration treatment provided moderate protection, where disease incidence was recorded 13.33% at 6 days, increasing to 26.66% after 10 days, whereas SiO_2NPs at 25 ppm concentration was less effective, showing a disease incidence of 60% after 10 days.

B- Effect of Chitosan and Silicon Nanoparticles on the severity of date fruit rot.

The results presented in Fig. 10 revealed that all tested concentrations of chitosan and silicon nanoparticles significantly reduced the disease severity compared to the control. Disease severity in the control was reached 100% after 6 days of incubation, whereas the lowest disease severity was recorded with both ChNPs at 100 ppm and SiO_2NPs at 100 ppm concentration treatments, which remained below 7% and 2%, respectively, even after 10 days of incubation. Moreover, the effectiveness of both agents decreased gradually with low concentration and the length of the incubation period, where disease severity was recorded as 40% and 30% for both ChNPs at 100 ppm and SiO_2NPs at 100 ppm concentration, respectively, even after 10 days.

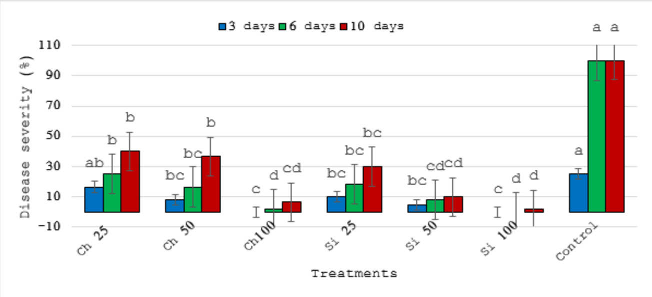

Fig. 10. Effect of treatments 3,6 and 10 days on the development of disease severity (%)
L.S.D. at 5% for: 3 days= 11.77, 6days=14.92 and 10 days=26.20. Columns with the same letters do not differ significantly according to LSD test ($P \leq 0.05$).

C- Effect of Chitosan and Silicon Nanoparticles on the weight loss of date fruits.

The results presented in Fig. 11. observed that a significant decrease in loss of weight was all treatments compared with the control, which recorded the highest loss of weight (7.33% and 8% after 6 and 10 days, respectively), while the lowest loss of weight was obtained with chitosan nanoparticle treatments, particularly ChNPs at 100ppm concentration, which maintained weight loss below 0.5% throughout the storage period. Silicon nanoparticle treatments also showed positive effects, although less effective than chitosan, with SiO_2NPs at 25 ppm concentration recording the highest loss of weight among treated fruits (8% after 10 days).

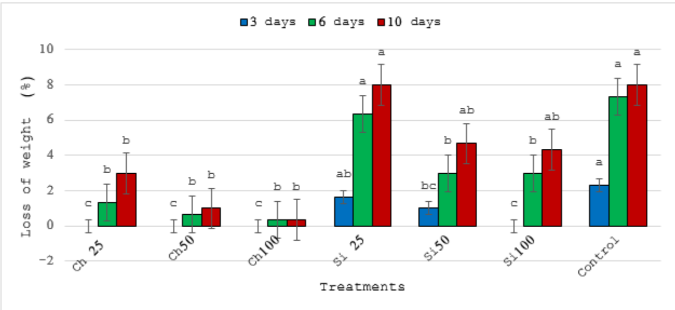

Fig. 11. Effect of treatments 3,6 and 10 days on the development of date fruit loss of weight (%)
L.S.D. at 5% for: 3 days= 1.26, 6days=2.78 and 10 days=4.90. Columns with the same letters do not differ significantly according to LSD test ($P \leq 0.05$).

D- Effect of Chitosan and Silicon Nanoparticles on total soluble solid (TSS)

The results in Fig. 12 show that treatments with chitosan and silicon nanoparticles significantly increased TSS content compared with the control (10.17). The highest TSS content was observed in SiO_2NPs at 100 ppm (16.53), followed by ChNPs at 100 ppm (15.33) and SiO_2NPs at 50 ppm (15.03). On the other hand, the lowest TSS content was recorded with ChNPs at 25 ppm (11.60) and SiO_2NPs at 25 ppm (11.40).

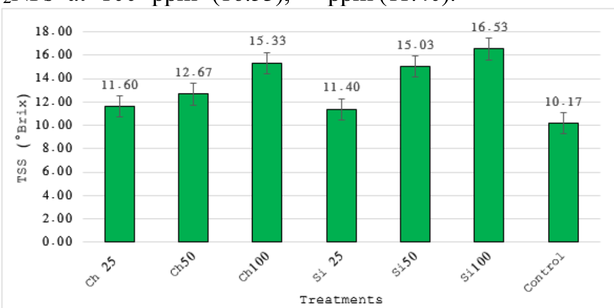

Fig. 12. Effect of chitosan and silicon nanoparticles treatments on date fruit total soluble solid (TSS)
L.S.D. at 5%: 3.60. Columns with the same letters do not differ significantly according to LSD test ($P \leq 0.05$).

Discussion

Our study shown that *A. niger* was the dominant species during isolation process that match with the result of Abo-El-Saad *et al.*, 2023 wich mentioned that the examination of infected date samples showed the infected specimens belong to the fungus *Aspergillus niger*. M Hussein

2022 referred to Specifically nine isolates of *A. niger* were isolated from date palm fruits. In the current study, the ITS sequence of the isolate (AUMC16164) showed 100% identity and 98–100% coverage with several *A. niger* strains deposited in GenBank, indicating that this isolate belongs unequivocally to the *A. niger* species complex. These findings are consistent with previous reports where *A. niger* isolates were successfully identified and phylogenetically clustered with reference strains using ITS sequences (Samson *et al.,* 2014). Also, this result was agreement Al-Mutarrafi *et al.,* 2019 showed the molecular identification of fungal isolates associated with soft dates that the most dominant isolated fungi were *Aspergillus niger* (100%). The pathogenicity test of *Aspergillus niger* AUMC16164 clearly demonstrated its ability to cause typical black mold rot symptoms on date fruits these results are consistent with previous reports identifying *A. niger* as a major postharvest pathogen of black mold, caused by *Aspergillus niger*, as the main fungal disease affecting Piarom dates in Iran (Goudarzi et al.,2022). In this study indicates the potential of chitosan and silicon nanoparticles as eco-friendly alternatives to fungicides for controlling *A. niger* fruit rot in dates. chitosan and silicon nanoparticles significantly inhibited mycelial linear growth *in vitro* and reduced disease incidence and severity *in vivo,* suggesting that these nanoparticles inhibit pathogens. The *in vitro* assay showed that growth inhibition was concentration-dependent, with the highest suppression observed in chitosan and silicon nanoparticles at 100 ppm. These results are agreement with earlier reports on the antifungal activity of chitosan, which obstructs fungal cell membranes, and activates defense-related enzymes in host tissues (El Ghaouth *et al*., 1992; Rabea *et al*., 2003). The *in vivo* assay Similarly, silicon has been shown to enhance plant resistance by reinforcing cell walls and triggering the accumulation of phenolic compounds and antioxidant enzymes, thereby reducing fungal infection (Epstein, 1999; Ma & Yamaji, 2006; Rodrigues *et al*., 2005). The high inhibition percentages recorded in this study align with the protective effects of silicon and chitosan reported in other fruit crops, including grapes, citrus, and cucumbers (Palou *et al*., 2016). The results on the fruits in vivo further confirmed the protective role of chitosan and silicon nanoparticles. At concentration 100 ppm, ChNPs reduced disease incidence to 26.6% and SiO_2NPs to 6.6% after 10 days, compared to 100% in control. These reductions in disease incidence and severity highlight the potential of nanoparticles in extending postharvest shelf life and minimizing losses. Similar trends were observed by Saqib *et al*. 2020, who reported that chitosan-based nanoparticles effectively inhibited postharvest pathogens in different fruits. Moreover, the antifungal activity of ChNPs observed in this study agrees with findings of El-Mohamedya *et al*. 2019, who demonstrated their effectiveness against different plant pathogenic fungi. Chitosan and silicon nanoparticles as eco-friendly of provides a safe alternative to fungicides, which are increasingly restricted due to health and environmental concerns (Wild & Gong, 2010). Considering the high economic value of date palm fruits in Egypt and other regions, implementing such sustainable strategies can contribute to reducing postharvest losses while ensuring food safety. In addition to disease inhibition, chitosan and silicon nanoparticles contributed to enhanced fruit quality by Maintaining fruit weight and total soluble solids (TSS), maintain nutritional attributes of date fruits maintaining fruit weight and enhancing TSS content. The ability of silicon to Maintaining weight may be related to its role in improving fruit firmness and reducing transpiration rates (Fawe *et al*., 1998; Epstein, 1999).

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فعالية جسيمات السيليكون والشيتوزان النانوية كعوامل صديقة للبيئة ضد (*Aspergillus niger*) مسبب تعفن ثمار البلح

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الملخص

تعد أمراض ما بعد الحصاد من أهم المعوقات التي تؤثر سلبًا على جودة وتسويق ثمار البلح. ويعتبر الفطر *Aspergillus niger* من أكثر المسببات المرضية خطورة ويسبب العفن الأسود. هدفت هذه الدراسة إلى تقييم الفعالية لكل من جسيمات الشيتوزان النانوية وجسيمات السيليكون النانوية كبدائل صديقة للبيئة للمبيدات الكيميائية. تم عزل وتشخيص المسبب المرضي مورفولوجيًا وتأكيده جزيئيًا كفطر *A. niger*. كما تم التحقق من نجاح تخليق جسيمات الشيتوزان والسيليكون وامتلاكها خصائص نانوية باستخدام المجهر الإلكتروني النافذ (TEM) وتقنية حيود الأشعة السينية (XRD) أظهرت الاختبارات المعملية كفاءة عالية في تثبيط النمو الميسليومي للمسبب المرضى، حيث سُجِّلت أعلى نسبة تثبيط عند تركيز ١٠٠ جزء في المليون لكل من نانو سيليكون (٩٦,٣٠٪) ونانو شيتوزان (٩٢,٥٩٪). وعند التطبيق على ثمار التمر، تبين أن المعاملات بكلا الجسيمات النانوية أدت إلى خفض ملحوظ في شدة المرض ونسبته. ففي تركيز ١٠٠ جزء في المليون، حققت نانو سيليكون ونانو شيتوزان أدنى نسبة إصابة (٦,٦٦٪ و٢٦,٦٦٪ على التوالي) بعد مرور عشرة أيام من الإصابة مقارنة بالكنترول. بالإضافة إلى ذلك، ساعدت المعاملات في الحفاظ على وزن الثمار ومحتواها من المواد الصلبة الذائبة الكلية (TSS)، مما يشير إلى تحسن في الجودة بعد الحصاد. وتشير النتائج إلى إمكانية استخدام جسيمات الشيتوزان والسيليكون النانوية كعوامل آمنة ومستدامة في مكافحة العفن الأسود الذي يسببه فطر *A. niger* في ثمار البلح، مما يوفر بديلاً واعدًا للمبيدات الكيميائية.

الكلمات الداله: ما بعد الحصاد، تعفن الثمار، الجسيمات النانوية