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Chitosan enriched with ZnO—nanoparticles fabricated using *Synadenium glaucescens* (Pax) aqueous leaf extract maintains postharvest quality of banana

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ABSTRACT

Applications of edible coatings containing metallic nanoparticles for the preservation of post-harvest fruit quality have emerged as one of the most preferable strategies because of their enhanced antimicrobial properties. In the current study, zinc oxide nanoparticles were synthesized using *Synadenium glaucescens* leaf extract and added to chitosan for the post-harvest quality preservation of banana. The synthesized zinc oxide nanoparticles (ZnOSydlNPs) were characterized using scanning electron microscopy (SEM), transmission electron microscopy (TEM), elemental dispersive x-ray (EDX) and X-ray diffraction (XRD) techniques. The nanoparticles were found to form large particles due to aggregations of small particles of an average size of 11 ± 4 nm. The coating solution containing a mixture of chitosan and zinc oxide nanoparticles exhibited higher antimicrobial effects against *Escherichia coli, Staphylococcus aureus, Puccinia asparagi* and *Candida albicans* compared to chitosan. The inhibition diameters of chitosan and chitosan-ZnOSydlNPs against *E. coli* were 6 and 15 mm, respectively. Similarly, the average inhibition diameters of chitosan, chitosan-ZnOSydlNPs (0.1%) and chitosan-ZnOSydlNPs (0.3%) against *Staphylococcus aureus, Puccinia asparagi* and *Candida albicans* were 10 ± 2, 15 ± 0.5 and 16 ± 3 mm, respectively. The banana coated with chitosan-ZnOSydlNPs solutions exhibited higher titratable acid (maleic) than control and chitosan-coated samples. Additionally, banana coated with chitosan-ZnOSydlNPs films showed lower total soluble solids, weight loss and ripening index compared to chitosan-coated and control samples. The findings from the current study indicated that ZnOSydlNPs incorporated in polymeric materials (chitosan) could serve as a potential preservative of post-harvest qualities for banana and related fruits.

1. Introduction

Banana (*Musa* spp.) is one of the most consumed fruits due to its taste, nutritional value, and convenience. Consequently, it is a cheap and reliable source of carbohydrates, antioxidants, and other micronutrients. However, the fruit is highly perishable because of its high water content and susceptibility to microbial attacks. The fruits produce large quantities of ethylene gas, which leads to rapid changes in their physiochemical properties such as color, texture, aroma, chemical composition, and respiration rate (Maduwanthi & Marapana, 2019). The spoilage of banana fruits can also be caused by their high oxygen consumption, conversion of sugars to starch, chlorophyll degradation, and relocation of micronutrients. Thus, the post-harvest preservation of banana is highly required to maintain their quality and global supply.

Different techniques such as physical preservation, chemical treatment and biological control have been effectively used for the post-harvest quality preservation of banana (Al-Dairi, Pathare, Al-Yahyai, Jayasuriya & Al-Attabi, 2023). However, most of these techniques cannot meet the current development of the supply chain due to their high cost and selectivity (Han et al., 2021). The use of physical preservation techniques such as cold chain may cause chill injuries to the fruits (Han et al., 2021), while genetic engineering normally requires high capital and approval for human use (Jiang et al., 2021). Thus, cheap, eco-friendly, and simple preservation techniques are needed for post-harvest preservation of banana fruits.

The application of biodegradable coatings is among the highly acceptable, cheap and nontoxic post-harvest preservation methods (Guarnieri et al., 2024; Hassan, Chatha, Hussain, Zia & Akhtar, 2018;

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Maftoonazad, Ramaswamy & Marcotte, 2008). The coatings have also been reported to be carriers for several functional ingredients, such as antibacterial agents and antioxidants that prevent the growth of microorganisms and oxidation reactions in fruits and vegetables (Xing et al., 2020). The coatings extend the shelf life of fruits while enhancing their appearance and quality. The coatings form a barrier on the fruit surface that inhibits gas diffusion, respiration rate and water loss (Panahirad, Naghshiband-Hassani, Ghanbarzadeh, Zaare-Nahandi & Mahna, 2019; Shah & Hashmi, 2020). The use of synthetic polymers such as polyfluoroalkyl substances for post-harvest preservation is associated with detrimental effects on human health such as decreased fertility, increased risk of obesity and cancer (breast, liver, testicular, kidney) (Gaines, 2023; Manojkumar, Pilli, Rao & Tyagi, 2023). Consequently, applications of bio-based coating materials such as polysaccharides such as chitosan and alginate have gained significant attention (Shiri et al., 2013; Umbayda, Funga & Mwakalesi, 2024; Wang et al., 2017; Wu, Wu & Hu, 2024).

Chitosan, a biopolymer derived from chitin, has emerged as a promising edible coating material for post-harvest quality preservation of various fruits due to its biocompatibility, film-forming ability, and antimicrobial activity (Elsabagh et al., 2023; Elsabee & Abdou, 2013; Guarnieri et al., 2024; Triunfo et al., 2023). The addition of metallic nanoparticles to the chitosan is known to produce increased preservation properties (Xing et al., 2020). Among the metallic nanoparticles, Zinc oxide (ZnO) nanoparticles have gained significant attention because of their broad spectrum antimicrobial, antioxidant, and gas barrier properties, which can effectively inhibit microbial growth and delay ripening in fruits and vegetables (Anugrah, Alexander, Pramitasari, Hudiyanti & Sagita, 2020; Welikala, Wijesinghe & Thiripuranathar, 2023). Thus, the synergistic effects of ZnO nanoparticles and chitosan can provide a multifunctional barrier against microbial pathogens that reduces enzymatic browning and maintains the overall freshness of bananas during storage (Taghipour, Nia, Hokmabadi & Martínez-Gómez, 2024).

Zinc oxide nanoparticles prepared using conventional methods are highly limited in their use due to the hazardous properties of chemicals employed in their fabrication (Chan, Pang, Lim & Chong, 2021; Naseer, Aslam, Khalid & Chen, 2020). Consequently, applying plant extracts to synthesize zinc oxide nanoparticles has been the preferred technique because most phytochemicals are renewable, nontoxic and environmentally friendly (Al-darwesh, Ibrahim & Mohammed, 2024). *Synadenium glaucescens* is a plant species rich in bioactive compounds with various pharmacological properties (Rukunga, Gunnar & Kofi-Tsekpo, 1990). Extracts from the plant were reported to be used for treating various viral and bacterial diseases (Credo et al., 2022; Msengwa et al., 2023). The phytochemicals such as alkaloids and flavonoids are known to be contained in the leaf extract from the plant (Basnet, Chanu, Samanta & Chatterjee, 2018). Similar compounds sourced from other plants were previously used to synthesize zinc oxide nanoparticles with antimicrobial properties that permitted their use for the post-harvest quality preservation of fruits (Arroyo et al., 2020; La et al., 2021; Le et al., 2021). Similarly, silver nanoparticles with antimicrobial properties fabricated using the aqueous root extract from *Synadenium glaucescens* are known (Mwakalesi & Mushi, 2024). However, there is limited information on synthesizing ZnO nanoparticles for post-harvest quality preservation of fruits using phytochemicals sourced from *Synadenium glaucescens*. Thus, the green synthesis of ZnO nanoparticles using phytochemicals derived from *Synadenium glaucescens* leaf extract and their use for post-harvest preservation of banana were reported in the current study. The findings from the study are expected to advance the knowledge on the use of greenly synthesized nanoparticles for post-harvest preservation of perishable fruits.

Fig. 1. Photograph showing *Synadenium glaucescens* leaves.

2. Materials and methods

2.1. Materials

Synadenium glaucescens leaves were collected from the Chemistry and Physics laboratory in SUA. Zinc acetate (99.9%), Glacial acetic acid (≥ 99%), $CaCl_2$ (≥ 97%) NaOH (granular) and H_2SO_4 (96%) were purchased from Sigma-Aldrich, Dorset, UK. Chitosan 90% deacetylated Acetic acid (TIENS Chitosan capsule), Sterile LB agar (Oxoid, Basingstoke, UK) Gentamycin (Abbott Healthcare Pvt. Ltd) and Ketoconazole (IndiaMART, India), ethanol (>99% purity), acetone (Pearlchemical, Mumbai India), phenolphthalein indicator. This study also employed the use of materials such as a centrifuge machine (Thermo Fisher Scientific Inc, America), blender (Mister Chef® 2200 W, Amazon), filter paper (Whatman filter paper No. 1), and digital refractometer (PAL-1™, ATAGO-co-Limited, Japan).

2.2. Preparation of Synadenium glaucescens leaf extract

Synadenium Glaucescens leaves (Fig. 1) were washed with tap water to remove attached solids and then rinsed using distilled water. The cleaned leaves were then dried in an oven at 50 °C until a constant mass was obtained. The dried leaves were ground to produce a powder that was used for the extraction of phytochemicals by stirring the powder (10 g) in 100 mL of distilled water at 80 °C for 30 min (Mwakalesi, 2023; Mwakalesi & Mushi, 2024; Mwakalesi & Nyangi, 2023). The resultant mixture was filtered using the Whatman filter paper No. 1 to obtain a clear solution used to prepare ZnOSydlNPs.

2.3. Synthesis of zinc oxide nanoparticles

ZnOSydlNPs were synthesized following the previously reported procedures (Hameed et al., 2023). Briefly, the aqueous extract (20 mL) was added to a 0.02 M zinc acetate solution (80 mL), and a mixture was stirred using a thermostatic water bath at 100 oscillations per minute. The pH of the mixture was increased to 12 by the addition of NaOH (0.1 M). Up on continued stirring, the formation of pale-yellow precipitates was observed. The mixture was stirred further for 5 h, and centrifuged at 4000 rpm for 15 min. The supernatant was discarded and precipitates were washed with distilled water and ethanol to remove unreacted impurities. The collected precipitates were then dried in an oven at 60 °C and calcinated at 400 °C for 2 h to produce white precipitates of zinc oxide nanoparticles (ZnOSydlNPs).

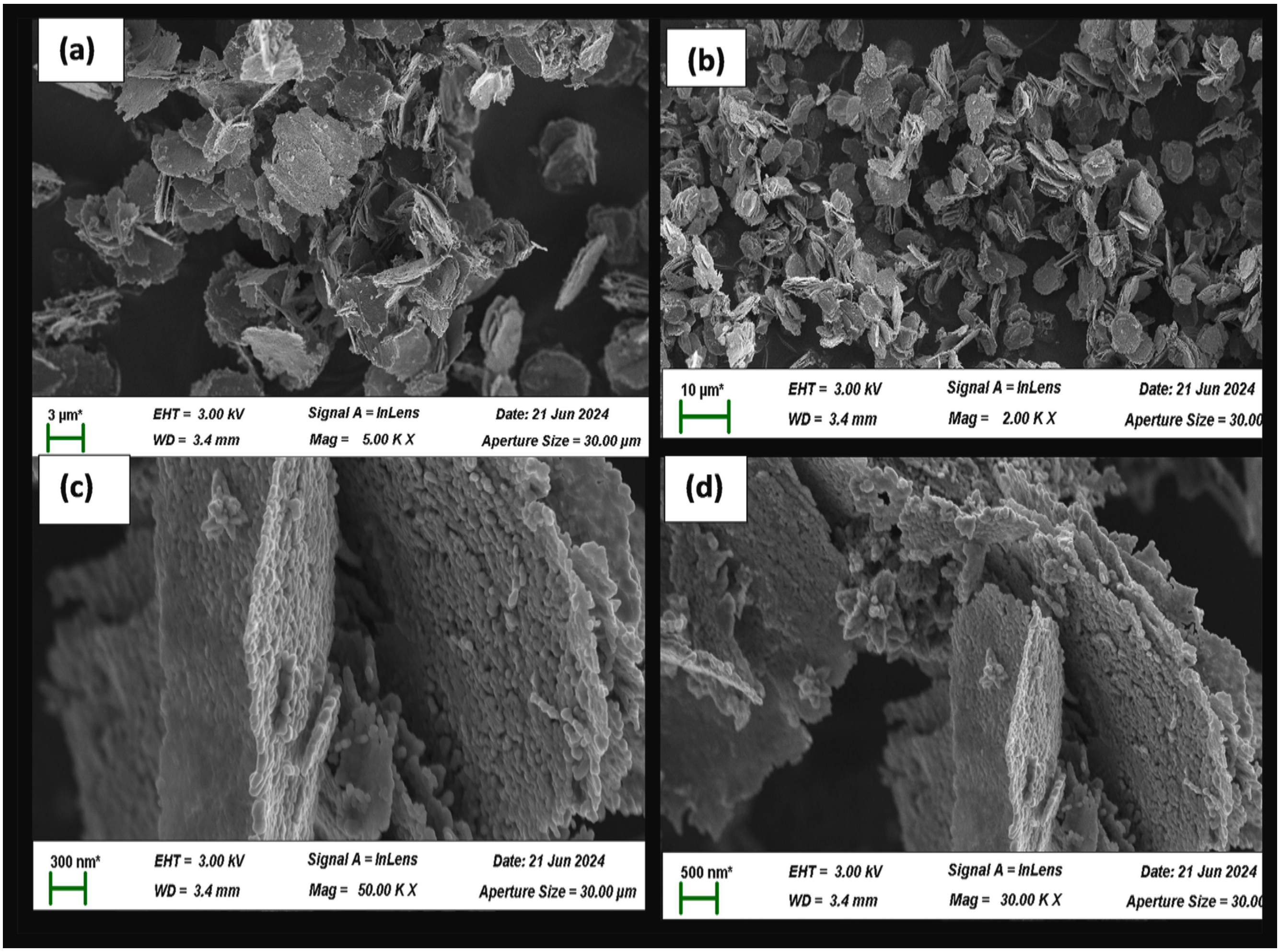

Fig. 2. SEM images of ZnOSydlNPs at different magnifications.

2.4. Characterization of ZnOSydlNPs

The fabricated ZnOSydlNPs were characterized using XRD, SEM, and EDX techniques. The XRD equipped with Cu-K radiation and a wavelength of 1.7903 Å was employed to examine the crystallinity of the nanoparticles. The SEM analysis was used to determine the morphology of the nanoparticles after their deposition on a glass slide using acetone and dried to form a thin layer. The elemental composition analysis was analysed using the EDX detector fixed to the SEM instrument.

2.5. Preparations of chitosan-ZnOSydlNPs coating solution

Coating solutions were prepared by incorporating ZnOSydlNPs into a polymeric material (chitosan) (Kanmani & Rhim, 2014; Le et al., 2021). Briefly, ZnOSydlNPs 0.3 g and 0.6 g were separately prepared in 0.3 L of a solution containing 1% w/v chitosan prepared in 1% v/v acetic acid. The chitosan solution was prepared by dissolving chitosan (3 g) in 1% v/v acetic acid solution (0.3 L) at 60 °C. The resulting mixture was stirred at 80 °C for about 5 min and cooled to room temperature (García-García et al., 2023). The resultant homogeneous mixtures of 0.1% w/v ZnOSydlNPs (A) and 0.3% w/v ZnOSydlNPs (B) were used to prepare edible coatings for the preservation of banana fruits.

2.6. Application of coatings formulation on banana fruits

Before coating, banana fruits were washed with distilled water to remove any dust on the surface and immersed in a 1% $CaCl_2$ solution for 5 min. Then, they were drained and left at room temperature for 4 h to allow excess solution to drip out. The prepared coating solutions were applied to banana surfaces using a dipping method. One group of banana (control samples) was immersed in distilled water and then air-dried. On the other hand, other banana fruits were dipped into solution A and B. After coatings, banana were air-dried at ambient temperature. Both coated and control samples were stored in a post-harvest shed at 28 °C. The fruit quality parameters, including titratable acidity, total soluble solids, weight loss, and ripening index, were analyzed. The measurements were performed at 5-day intervals for both control and coated samples.

2.7. Antimicrobial properties of chitosan-ZnOSydlNPs mixture

The antimicrobial activities of chitosan, solutions A and solution B were analysed using a disk-diffusion agar assay. The representative microbes used in the current experiment were *Escherichia coli, Staphylococcus aureus, Puccinia asparagi* and *Candida albicans*. Sterile L.B. agar was inoculated with 100 µL microbial cell suspension at 10^5 CFU/mL. To wells of about 10 mm, 100 µL of chitosan, solutions A, solution B, and standards (gentamycin or ketoconazole) were added. The plates were incubated for 24 h at 37 °C, and the performance of coated solutions was determined by measuring the diameters of inhibition zones.

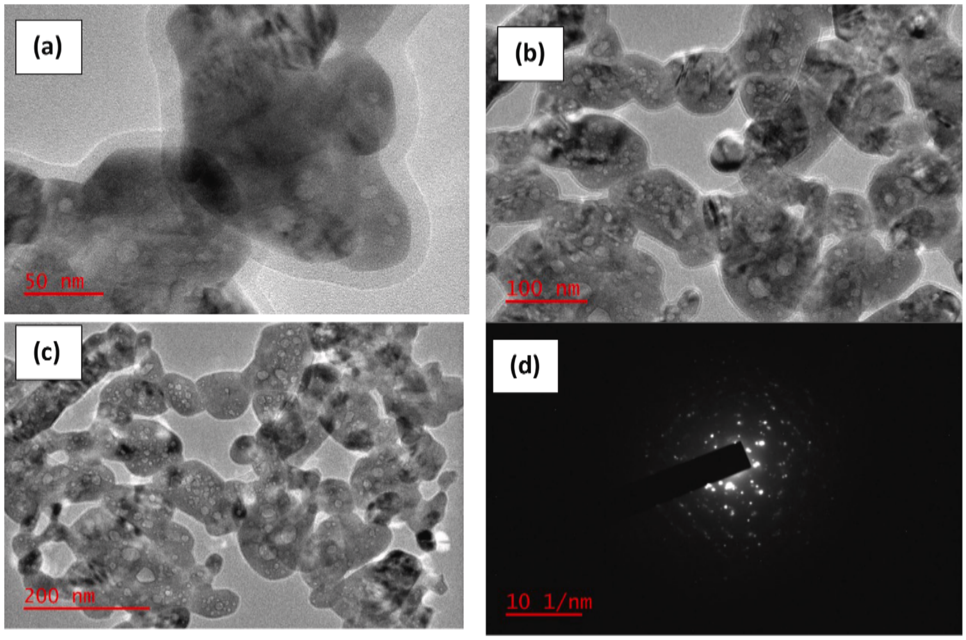

Fig. 3. TEM images of ZnOSydlNPs at different magnifications **(a)** – **(c)**, the selected area electron diffraction (SAED) pattern **(d)**.

2.8. *Preservation of banana*

2.8.1. *Determination of titratable acidity (TA)*

The titratable acidity (TA) was analyzed using titration (Volmer et al., 2017). Briefly, banana pulp (100 g) collected from each treatment was blended in 50 mL of boiled distilled water for one hour. The resultant mixture was centrifuged at 6000 rpm for 5 min and filtered through a filter paper (Whatman filter paper No. 1) to obtain a clear filtrate that was titrated against 0.1 M NaOH in the presence of phenolphthalein (0.1%) as the indicator. The results of TA were presented in the percentage of malic acid per 100 g banana sample (Kumar et al., 2019).

2.8.2. *Total soluble solid (TSS)*

The total soluble solid was determined by placing the banana pulp drops on the portable digital refractometer's prism (ATAGO-co-Limited, Japan). The results for total soluble solid were expressed as °Brix. The refractometer was standardized at 0 °Brix using distilled water.

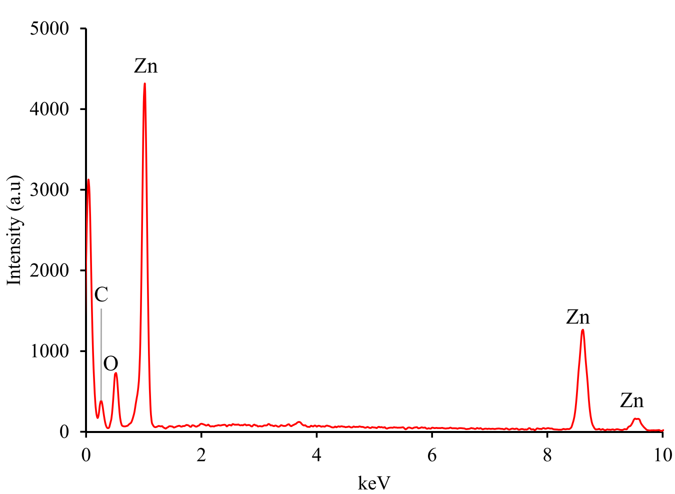

Fig. 4. EDX spectrum of ZnOSydlNPs.

2.8.3. *Determination of physiological weight loss (PWL)*

The weight loss from each group was determined by measuring the weight of banana at time zero and after storage time using a digital balance. The weight loss was expressed as a percentage of physiological weight loss (Eq. (1)) (Majidi, Minaee, Almasi & Mostofi, 2011).

$$\mathrm{PWL} = (\text{weight at nth day} - \text{weight at 0th day})/\text{weight on 0th day} \times 100\% \quad (1)$$

2.8.4. *Ripening index (TSS/TA)*

The ripening index was calculated by dividing TSS by TA. as expressed in Eq. (2) (Majidi et al., 2011; Simkova et al., 2024).

$$\text{Ripening index} = \text{Total soluble solids(TSS)}/\text{Titratable acidity(TA)} \quad (2)$$

2.9. *Statistical analysis*

The experiments were conducted in triplicate, and results were reported as mean ± standard deviations. The statistical analysis was performed using SPSS 25.0 (IBM, USA). The one-way analysis of variance (ANOVA) followed by Duncan's test was used to determine the significant difference between treatments ($p < 0.05$).

3. Results and discussion

3.1. *Characterization of synthesized ZnOSydlNPs*

3.1.1. *Morphological analysis*

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to determine the surface morphology, size, and shape of ZnOSydlNPs. The SEM images in Fig. 2**(a)-(b)** showed that the nanoparticles exhibited homogeneous shape and size. The agglomeration of smaller particles to form larger particles was observed (Fig. 2 **(c) – (d)**). As a result, the morphology of the nanoparticles reported in the current study significantly differs from those reported in other studies, such as nanorods, wires, needles, helixes, springs, rings, nanoplates and snowflakes (Rezaei, Katoueizadeh & Zebarjad, 2022). The observed agglomeration of the nanoparticles is likely to be attributed to collisions of particles caused by oscillations that were used to mix the solution during the synthesis process (Karsch & Kronenburg, 2023). Zinc

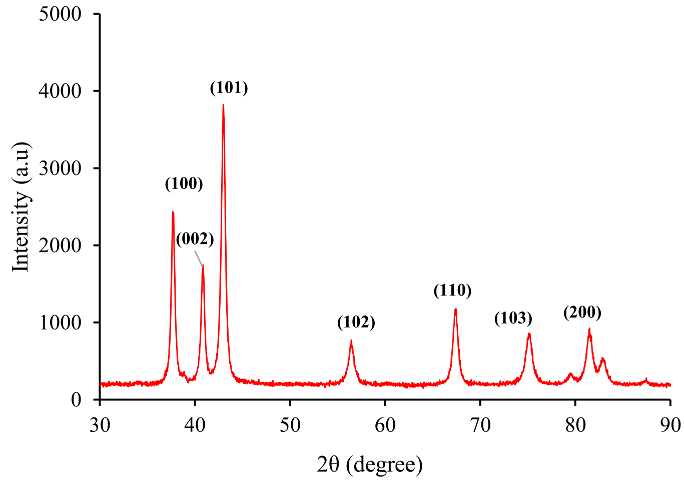

Fig 5. XRD pattern of ZnOSydlNPs.

oxide nanoparticles of different sizes and morphologies due to different temperatures, mixing methods and stoichiometric ratios were previously reported (Rezaei et al., 2022).

The agglomeration of nanoparticles was also observed in the TEM images (Figs. 3**(a)-(c)). Similarly,** the bigger nanoparticles were observed to be formed by aggregations or overlapping of smaller particles to each other. Most aggregated smaller nanoparticles were spherical, with an average size of 11 ± 4 nm (**Fig. S1**). The findings of the selected area electron diffraction (SAED) image (Fig. 3**(d))** also showed that the fabricated nanoparticles contained sharp spots as a possible indicator of polycrystalline nature with the symmetrical orientation of the nanoparticles. The formation of sharp spots in the SAED image as a possible indicator for the formation of polycrystalline zinc oxide nanoparticles was previously reported (Islam et al., 2024).

3.1.2. Energy dispersive X-ray spectroscopy (EDX)

The energy dispersive X-ray (EDX) analysis was also performed to determine the elemental composition of ZnOSydlNPs. The findings in Fig. 4 showed that the prepared sample comprised a zinc-containing compound in an oxide form. The strong peaks due to the zinc element were observed at 1.02, 8.6 and 9.6 keV. Additionally, the peak for the oxygen atom was observed at 0.54 keV. Thus, the observed peaks due to zinc and oxygen indicate that ZnOSydlNPs were successfully synthesized. The peak due to carbon at 0.28 keV was a possible indicator of phytochemicals originating from the plant extract. Similar EDX findings were reported for zinc oxide nanoparticles synthesized using *Eucalyptus globulus* Labill. leaf extract (Barzinjy & Azeez, 2020).

3.1.3. X-ray diffraction (XRD)

The dried sample of the fabricated zinc oxide nanoparticles was used for the XRD analysis using the Cu-K radiation (λ=1.7903 Å) over theta (2θ) range of 0 - 90°. The results in Fig. 5 showed the appearance of sharp peaks, which is a possible indicator of the high purity and crystallinity nature of the fabricated zinc oxide nanoparticles. The theta (2θ) planes of diffraction peaks were located at 37.76°, 40.93°, 42.99°, 56.64°, 67.48°, 75.43°, 81.6° and 83.22°. The observed peaks correlated with the hexagonal shape of ZnONPs with a space group p 63 mc (Ahsbahs & Sowa, 2006). The average crystalline size of zinc oxide nanoparticles was 22 nm, as calculated by the Debye–Scherrer's equation (Rabiei et al., 2020). The difference in the size observed between XRD and TEM was possibly attributed to the fact that the XRD provided information about grain size. Consequently, the larger size exhibited by the XRD was possibly caused by polycrystalline formed by the coalescence of smaller grains (Pu, Niu, Wang, Liu & Zhang, 2022; Wu, Baltrusaitis, Gillan & Grassian, 2011).

Table 1
Zone of Inhibition (mm) for coating chitosan, solutions A and B against selected microbes.

Sample	Inhibition zone (mm)			
	E.coli	*S. aureus*	*P. asparagi*	*C. albicans*
Negative control	0	0	0	0
Positive control	16	14	12	27
Chitosan	6	11	8	12
Chitosan + ZnOSydlNPs (0.1%)	15	15	15	14
Chitosan + ZnOSydlNPs (0.3%)	15	15	21	14

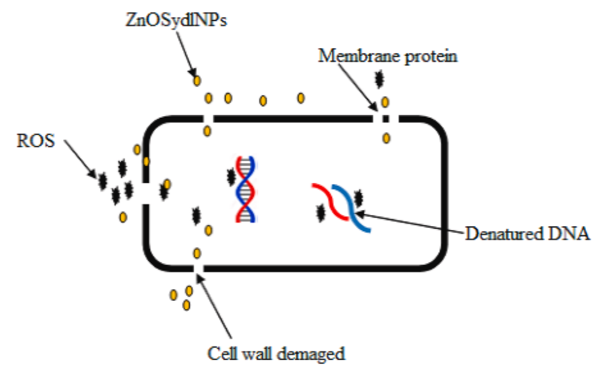

Fig. 6. A plausible mechanism for reactive oxygen species-mediated antimicrobial activity of chitosan-ZnOSydlNPs film.

3.2. Antibacterial and antifungal activities of chitosan-ZnOSglNPs

Microbial contamination is among the major causative factors for the deterioration of post-harvest fruit quality (Alegbeleye, Odeyemi, Strateva & Stratev, 2022). Thus, preliminary experiments involved the study of potential antibacterial and antifungal properties of fabricated chitosan-zinc oxide nanoparticles. The findings (Table 1 **and Fig. S2 & S3)** revealed that chitosan alone showed moderate antimicrobial effects against selected bacteria and fungi. However, the antibacterial effects were lower for *E. coli* compared to *S. aureus*, similar to previously reported findings (Goy, Morais & Assis, 2015). The observed antimicrobial properties were likely caused by electrostatic interactions of charged chitosan molecules with membranes of the bacterial wall (Mirbagheri et al., 2024). The interactions can cause alterations in the cell membranes and the release of intracellular components. Chitosan can also bind with microbial enzymes and nucleotides to disrupt cell structures (Guarnieri et al., 2022). The results (Table 1) also indicated that the chitosan-fabricated nanoparticles produced a higher inhibition zone compared to chitosan alone. However, an insignificant improvement was observed when the amount of the nanoparticles in chitosan increased from 0.1 to 0.3%. The observation that higher antimicrobial effects were observed in the presence of ZnOSydlNPs indicates that the nanoparticles enhance the antifungal and antibacterial properties. A similar improved antibacterial properties of a chitosan polymer due to the addition of zinc oxide nanoparticles was previously reported (Rezaei, Pirsa & Chavoshizadeh, 2020). The improvement of antimicrobial properties is likely to be attributed to excessive accumulation of reactive oxygen species (ROS) in the target microorganisms due to the excessive stress produced by the combination of chitosan and the nanoparticles. The enhanced production of ROS can cause a series of damages to cellular structure and physiological metabolic processes, leading to the death of microorganisms (Fig. 6). Additionally, ZnO can release Zn^{2+} which can inhibit glycolytic enzymes through thiol group oxidation due to its high affinity to sulfur groups (Mendes et al., 2022). Therefore, the findings in the current study suggest that the combination of chitosan and zinc oxide nanoparticles is likely to produce a film with synergistic antimicrobial effects that can be applied for post-harvest

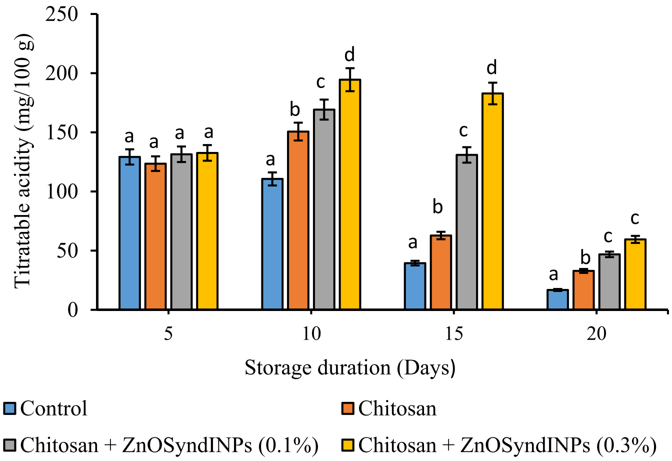

Fig. 7. Effect of chitosan and zinc oxide nanoparticles (ZnOSydlNPs) fabricated using *Synadenium glaucescens* leaf extract on titratable acidity of banana fruits along 20 days stored at ambient conditions. Data are expressed as mean ± standard deviation. The different letters on the same storage duration showed the significant difference ($P < 0.05$).

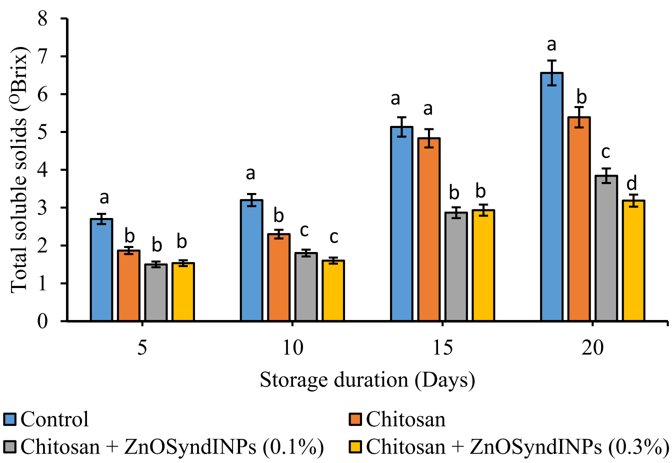

Fig. 8. Effect of chitosan and zinc oxide nanoparticles (ZnOSydlNPs) fabricated using *Synadenium glaucescens* leaf extract on total soluble solids of banana fruits along 20 days stored at ambient conditions. Data are expressed as mean ± standard deviation. The letters on the same storage duration showed the significant difference ($P < 0.05$).

preservation of fruits.

3.3. Application of ZnOSydlNPs for post-harvest preservation of banana

3.3.1. Titratable acidity

The titratable acid (TA) is an important parameter that indicates levels of organic acids such as citric and malic acids that determine the taste of fruits. Thus, the influence of the chitosan-ZnOSglNPs film on the amount of titratable acids in banana fruits was investigated. The findings (Fig. 7) indicated that the TA values decreased from 129.2, 123.5, 131.4667, and 132.6 mg/100 g sample on the 5th day to 16.7, 32.8, 49.9, and 59.5 mg/100 g sample on the 20th day for control, chitosan, chitosan-ZnOSydlNPs (0.1%) and chitosan-ZnOSydlNPs (0.3%), respectively. The observed decrease in TA values for the coated samples is significantly different ($P < 0.05$) from uncoated samples (Fig. 7). The decrease in TA values was possibly attributed to the degradation of acids that were used as substrates for enzymatic respiration reactions (Fagundes, Carciofi & Monteiro, 2013). As a consequence, the observed retention of TA for coated banana samples throughout the storage days is a possible indicator of reduced metabolic activities.

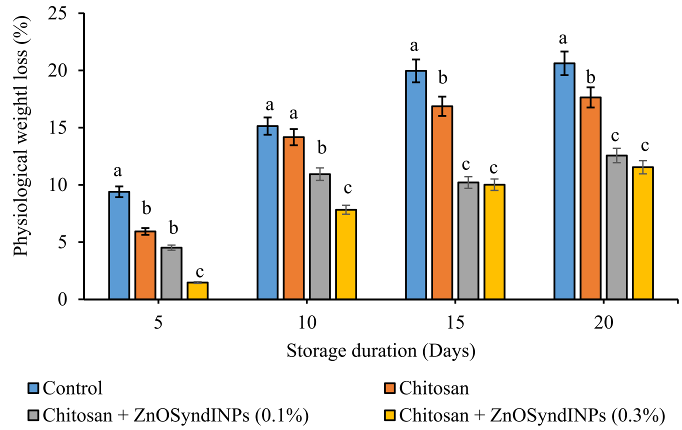

Fig. 9. Effect of chitosan and zinc oxide nanoparticles (ZnOSydlNPs) fabricated using *Synadenium glaucescens* leaf extract on physiological weight losses of banana fruits along 20 days stored at ambient conditions. Data are expressed as mean ± standard deviation. The letters on the same storage duration showed the significant difference ($P < 0.05$).

The capacity of chitosan to inhibit the growth of bacteria that can degrade fruit could also account for the increased levels of titratable acidity seen in banana coated with chitosan film when compared to control samples (Duan et al., 2019). Consequently, the organic coating used for preservation exhibited enhanced antibacterial capabilities due to the incorporation of zinc oxide nanoparticles into chitosan. Consequently, there was less banana deterioration, as seen by higher concentrations of titratable organic acids (Fig. 7). As a result, the results of this study show that adding ZnOSglNPs to chitosan results in a film that decreases respiration rates and increases antibacterial activity, hence inhibiting the breakdown of acids found in fruits.

3.3.2. Total soluble solid (TSS)

Total soluble solid is a possible indicator of the amounts of soluble compounds accumulated in a solution and it is also a useful indicator of fruit ripeness and sweetness (Magwaza & Opara, 2015). The influence of zinc oxide nanoparticles on the total soluble solids was also explored in the current study. The findings (Fig. 8) showed TSS values for all banana increased with increasing storage time. The increase in TSS values is a possible result of the hydrolysis of starch and other carbohydrates to yield soluble sugars such as glucose, sucrose and fructose (Alam, Hossain & Sarkar, 2020; Jodhani & Nataraj, 2021). Thus, the highest values of TSS were observed for the uncoated banana samples and a significant decrease of TSS values was observed in the presence of chitosan coating. The presence of ZnOSydlNPs in the edible coating further decreased the values for TSS. The TSS values on 15th day were observed to be 6.6, 5.4, 3.8 and 3.2 for control samples, chitosan, chitosan-ZnOSydlNPs (0.1%) and chitosan-ZnOSydlNPs (0.3%) coated samples, respectively. The significant difference observed for TSS values between control and coated samples was possibly caused by slow degradation of polysaccharides to simple sugar due to the limited respiration rate caused of the applied chitosan/chitosan-ZnOSydlNPs coatings. Other researchers have also reported the decreased TSS values in the presence of the chitosan edible coating (Li et al., 2019). Additionally, cherry tomatoes coated with chitosan containing zinc oxide nanoparticles exhibited lower TSS values than those coated with chitosan alone (Li et al., 2021). Therefore, the findings from the current study demonstrate that edible coating made of chitosan and ZnOSydlNPs yielded a film that can significantly reduce the degradation of polysaccharides contained in banana.

3.3.3. Physiological weight loss

The weight loss is caused by water loss due to the difference in water vapor pressure between the fruit surface and the environment. In this

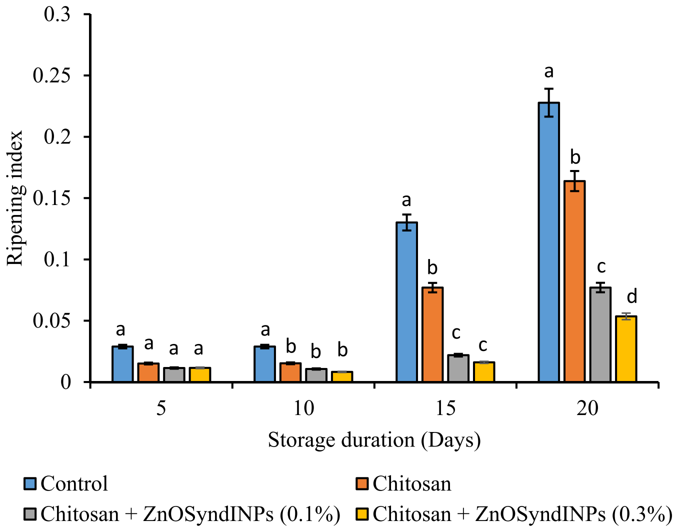

Fig. 10. Effect of chitosan and zinc oxide nanoparticles (ZnOSydlNPs) fabricated using *Synadenium glaucescens* leaf extract on the ripening index of banana fruits along 20 days stored at ambient conditions. Data are expressed as mean ± standard deviation. The letters on the same storage duration showed the significant difference ($P < 0.05$).

study, the effect of the chitosan-ZnOSydlNPs coating on the weight loss of banana fruits was investigated. The findings (Fig. 9) indicated that the weight loss in all treatments increased with the storage period. The observed weight loss is a possible result of water loss caused by the diffusion of moisture from the banana to the external environment due to respiration and transpiration. However, the application of chitosan film resulted in a decreased weight loss compared to the control group. The reduced weight loss observed is likely to be attributed to the ability of chitosan to form a protective barrier on the fruit surface that reduces water loss and slows down the rate of deterioration (Wantat, Rojsitthisak & Seraypheap, 2021). The presence of fabricated zinc oxide nanoparticles in the chitosan decreased further the weight loss of banana fruits compared to those treated with chitosan alone. On the 20th day, the weight loss of banana preserved with the film containing chitosan-ZnOSydlNPs 0.1% and 0.3% showed weight loss of 13% and 12%, respectively. The observed weight losses were lower compared to banana coated with chitosan alone (18%) and the control group (21%). The reduced weight loss in the presence of ZnOSydlNPs is likely to be associated with the hydrophobic properties of the nanoparticles that can modify the properties of chitosan coating and reduce water vapor permeability. The nanoparticles are also known to contain antimicrobial activities that can reduce weight loss by inhibiting the loss of carbon atoms due to the respiration process. A similar decreased weight loss due to the presence of zinc oxide nanoparticles in an edible coating was previously reported (La et al., 2021).

3.3.4. Ripening index

The ripening index is a crucial parameter reflecting the physiological and biochemical changes occurring in the fruit during the ripening process. It is also a possible indicator of the amounts of sugar and organic acids contained in fruits (Simkova et al., 2024). In this study, the ripening index was calculated using Eqn. (2) and the results (Fig. 10) demonstrated that the ripening index for treated and control samples increased with increasing storage time. The observation indicates that the ripening process occurred throughout the storage period. However, the samples treated with chitosan showed a lower ripening index compared to control samples. The delayed ripening of banana fruits due to coating with high molecular weight chitosan was previously reported (Wantat et al., 2021). The sample coated with the film made of chitosan-ZnOSydlNPs exhibited the lowest ripening index (Fig. 10). On the 15th day, the ripening index values for banana preserved with

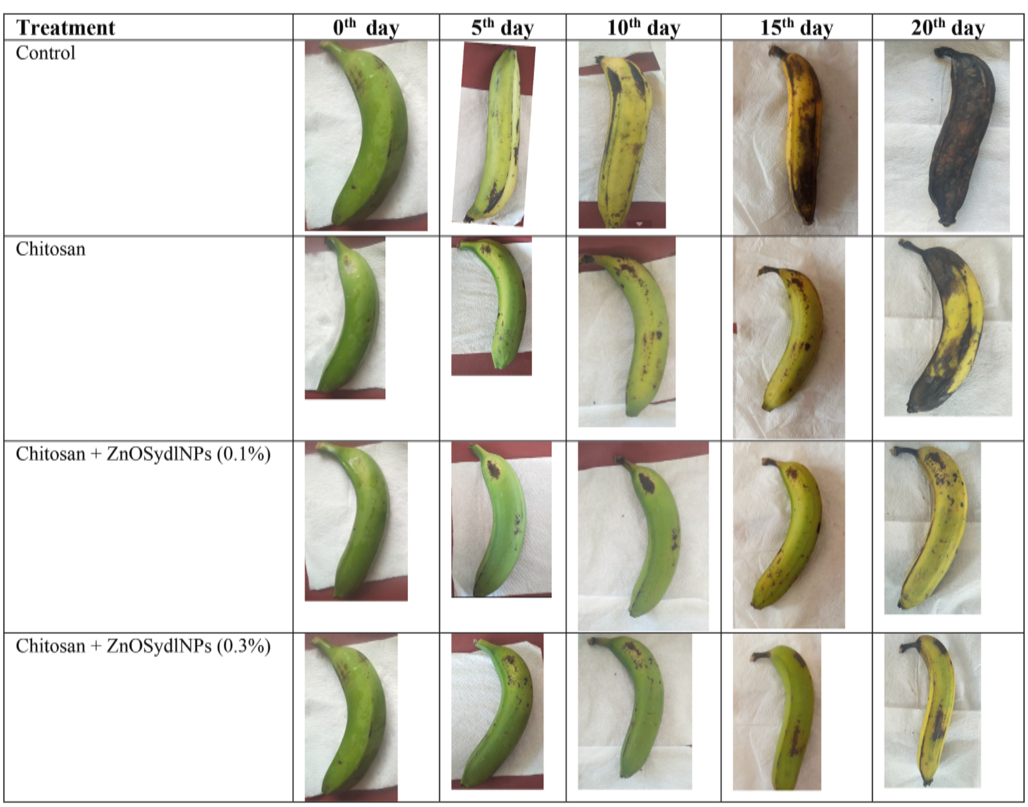

Fig. 11. Physical appearance of banana preserved with different coating solutions containing chitosan and zinc oxide nanoparticles (ZnOSydlNPs) fabricated using *Synadenium glaucescens* leaf extract.

chitosan-ZnOSydlNPs 0.1% and 0.3% were 0.021 and 0.016, respectively. The ripening index values were significantly lower compared to the control (0.1301) and samples coated with chitosan alone (0.077). Similarly, the findings from the visual analysis (Fig. 11) also indicated that banana coated with the film containing chitosan-ZnOSydlNPs exhibited smaller changes in physical appearance compared to control samples and banana coated with chitosan. The observation provide evidence that the applied chitosan-ZnOSydlNPs film offered higher protection against moisture loss and significantly reduced the ripening rate of banana. As a result, the morphological changes of peels in 20 days indicated that the fruits coated with the film containing chitosan-ZnOSydlNPs were highly preserved compared to control and chitosan coated samples. The observation indicates that the chitosan film enriched with ZnOSydlNPs provides excellent post-harvest quality preservation for banana fruits.

4. Conclusion

ZnOSydlNPs nanoparticles were successfully synthesized and incorporated in chitosan as an antimicrobial agent for banana's post-harvest quality preservation. The appearance of strong peaks in the EDX spectrum at 1.28 and 0.54 keV due to Zn and O indicated that the zinc oxide nanoparticles were successfully formed. The fabricated nanoparticles of an average size of 11 ± 4 nm aggregated to form large nanoparticles. The mixture of chitosan-zinc oxide nanoparticles displayed synergistic antimicrobial effects against *Escherichia coli, Staphylococcus aureus, Puccinia asparagi* and *Candida albicans*. The coatings prepared using chitosan and zinc oxide nanoparticles exhibited excellent performance in extending the shelf life of bananas under ambient conditions. The banana properties such as titratable acidity, total soluble solids, weight loss and ripening index significantly improved in the presence of the coating containing chitosan and nanoparticles compared to samples coated with chitosan alone. Similarly, the morphological changes showed that peels containing the film of chitosan-ZnOSydlNPs were highly protected against moisture loss and ripening. The current study's findings demonstrated that using chitosan-zinc oxide nanoparticle coating can be a promising alternative technology to preserve the post-harvest qualities of banana and related fruits. However, further investigations on the surface characterization of banana coated with the mixture are required to determine features of the organic film.

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Ethical statement- studies in human and animals

This work didn't use animals and/or human.

CRediT authorship contribution statement

Alinanuswe Joel Mwakalesi: Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tlehema Gwandu Umbayda:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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