Antibacterial and Antifungal Properties of Cassava Starch, Xanthan Gum and Zinc Oxide Nanoparticles Coating Solution for Banana (*Musa acuminate*) Preservation

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Abstract. Bananas are a nutritious energy source and a raw material for various products. However, their short shelf life poses a challenge, driven partly by microbial infection. This study evaluates an innovative edible coating made from cassava starch, xanthan gum, and zinc oxide nanoparticles (ZnONPs) to extend banana shelf life. The antibacterial properties of the coating were tested in vitro against *Escherichia coli* and *Staphylococcus aureus* using the disc diffusion method, with results confirmed by OD_{600} cell density measurements for microbial growth. Antifungal properties were tested against *Fusarium oxysporum f.sp. cubense* in vitro and further examined in vivo by dipping bananas in the coating solution. The antibacterial tests showed an optimal inhibitory concentration of 1.0% ZnONPs, while antifungal activity was significant at 2% ZnONPs. In vivo tests revealed no *F. oxysporum* growth, as it is non-pathogenic to banana peel. The study confirmed that the edible coating, developed to preserve freshness and reduce spoilage, effectively extended the shelf life of bananas. The coating solution perceived the synergistic effects of cassava starch as a protective layer, ZnONPs as antibacterial and antifungal agents, and xanthan gum for improved adhesion. This study highlights the potential of this edible coating as a solution for preserving bananas, outperforming currently available methods in addressing both local market demands and export opportunities.

1 Introduction

Edible coatings are innovative solutions designed to enhance the shelf life of perishable food items like fruits and vegetables by providing a protective barrier against various environmental factors [1]. These factors include oxygen and carbon dioxide, which, if not regulated, can accelerate spoilage; moisture, which can foster microbial growth; microbial contamination, which leads to food spoilage and potential health risks; light, which can degrade nutrients and alter food appearance; and temperature fluctuations that can compromise food integrity [2]. In general, without protective barriers, perishable items are prone to rapid spoilage, resulting in nutrient loss, undesirable texture changes, discolouration, and decreased food quality and safety [3]. These undesirable effects can increase food waste and economic losses, highlighting the importance of edible coatings in maintaining food quality and extending shelf life by mitigating environmental impacts [4].

The edible coating comprises various biopolymers, such as proteins, lipids, and carbohydrates [5]. These coatings can be tailored with additional functional ingredients like antioxidants and antimicrobials to enhance their effectiveness [5]. In this study, cassava starch and xanthan gum form a base for coating, combining their properties to form a layer that adheres to the food surface. Cassava starch, known for its clarity and lack of odour, is an excellent film-forming agent [6], while xanthan gum, a natural hydrocolloid, enhances mechanical strength and moisture barrier properties [7] . This synergy not only improves the barrier against moisture and gas exchange but also maintains the aesthetic and textural qualities of the coating solution produced. The textural quality of the coated produce can be further improved by increasing the antimicrobial properties of the coating. To elevate the antimicrobial functionality of the coating, zinc oxide nanoparticles (ZnONPs) can be incorporated, exploiting their broad-spectrum antimicrobial activity and ability to interact effectively with microbial cells [8,9]. ZnONPs, recognised as Generally Recognised as Safe (GRAS) by the FDA [10], contribute not only by enhancing the antimicrobial defences of the coating but also by improving its mechanical and barrier properties through their interaction with the biopolymer matrix [11]. Furthermore, their stability under heat and uniform dispersion characteristics within the polymer matrix enhance the overall effectiveness and safety of the coating, making it a viable alternative to traditional synthetic preservatives and extending the freshness of the coated items, such as bananas, without compromising food safety or quality [12].

Bananas are a widely consumed fruit known for their high nutrient and sugar content. Banana is Malaysia's second most planted fruit crop, with a total cultivation area of 27,577 hectares and an annual production of 330,601 metric tons, according to the Department of Agriculture Malaysia's 2022 Fruit Crops Statistics. The plantation of bananas has been steadily increasing yearly, reflecting its significant role in both the local and export markets as a key agricultural commodity. However, bananas are prone to have a short shelf life due to several biological factors [13]. These include their rapid ethylene-release rates, which trigger swift ripening post-harvest by softening the flesh as starches convert to sugars, and high respiration rates contribute to their quick spoilage [14]. This natural ripening process, along with the fruit's low pH, creates optimal conditions for microbial infections, such as those caused by *Escherichia coli*, *Staphylococcus aureus*, and various fungi like *Fusarium oxysporum*, leading to further deterioration in the form of dark peels, black spots, and decay [13]. These issues are worsened during handling, storage, and transportation, where microbial attacks can proliferate, severely impacting the fruit’s marketability and edibility [15].

Developing an edible coating solution that combines cassava starch, xanthan gum, and ZnONPs to extend the shelf-life of bananas presents a significant challenge, particularly given the limited research on the application of this combination for banana preservation. Recognising this gap, the present study evaluates the antibacterial and antifungal capabilities

of an innovative coating solution composed of cassava starch, xanthan gum, and zinc oxide nanoparticles and its ability to preserve bananas (*Musa acuminate*), a popular banana variety in Malaysia. This innovative coating solution offers a cost-effective, safe, and sustainable method to slow the rapid ripening process and extend the shelf life of bananas. By addressing the limitations of existing methods, this approach has the potential to enhance banana preservation and improve its accessibility in local markets, making it a promising alternative to current preservation techniques.

2 Materials and methods

2.1 Materials

Fresh and damage-free bananas (*M. acuminate*, maturity index = 1) were purchased from a local market (Kuala Pilah) and washed with distilled water before being left to dry at room temperature (25°C). Cassava starch (Cap Kapal ABC, Malaysia) and xanthan gum (Evachem, Malaysia) were obtained from a local market. Meanwhile, stock cultures of *E. coli* (ATCC25922) and *S. aureus* (ATCC43300) were provided by UiTM Cawangan Negeri Sembilan (Department of Food Technology, Faculty of Applied Sciences, Kampus Kuala Pilah). The stock culture of *F. oxysporum* was obtained from UPM (Department of Cell and Molecular Biology, Faculty of Biotechnology and Biomolecular Sciences). The chemicals and microbiological media used in this study include glycerol (Sigma-Aldrich, Germany), Muller Hinton broth (Oxoid, USA), Muller Hinton agar (Becton Dickinson and Company, USA), Potato Dextrose broth, Potato Dextrose agar. Except for the food-grade zinc oxide nanoparticles (US Research Nanomaterials Inc., USA), all other substances were chemical-grade and used without further purification.

2.2 Preparation of coating solution

The coating solution was prepared based on the method described by Bahrami *et al.,* [16] with slight modifications. Accordingly, 1% (w/v) of cassava starch was mixed with 0.5% (w/v) of xanthan gum, 10% (v/v) of glycerol, and varying concentrations of ZnONPs (0.5%, 1.0%, 1.5% and 2.0% (w/v)). Firstly, cassava starch was dissolved in distilled water at 90°C and stirred for 30 min. Separately, xanthan gum was dissolved in distilled water at room temperature (25°C) and stirred for 30 min. Both solutions were then mixed using a rotor-stator homogeniser at 10,000 revolutions per minute (rpm) for 2 min at room temperature (25˚C). Concurrently, ZnONPs were dispersed in distilled water at room temperature (25˚C) using an ultrasonic cleaner (60 Hz) for 10 min. Lastly, the cassava starch/xanthan gum mixture was combined with the ZnONPs solution and stirred at 400 rpm for 2 h. The prepared coating solutions were labelled as cassava starch and xanthan gum (CX), cassava starch, xanthan gum, and 0.5% ZnONPs (CSXGS-0.5ZnONPs), cassava starch, xanthan gum, and 1.0% ZnONPs (CSXG-1.0ZnONPs), and cassava starch, xanthan gum, 1.5% ZnONPs (CSXG-1.5ZnONPs) and 2.0% ZnONPs (CSXG-2.0ZnONPs).

2.3 Determination of antibacterial properties of the coating solution

The antibacterial properties of the coating solutions were determined using the disc diffusion method [17]. Firstly, *E. coli* (gram-negative) and *S. aureus* (gram-positive) were cultured separately in Muller Hinton broth at 37°C for 24 h. Afterwards, the bacterial cultures were inoculated in 0.9% (w/v) saline solution, and the turbidity of the colony suspension was

adjusted to equivalent to 0.5 McFarland standard [18]. Next, 0.1 mL of the bacterial suspension was transferred onto a Muller Hinton agar plate and spread evenly using a sterile L-shaped spreader. Subsequently, a single disc (Oxoid, USA) (diameter = 6 mm) was dipped into the coating solution for 10 sec following the concentration respectively and put onto the agar plate. For comparison purposes, streptomycin was used as a positive control, while sterile distilled water was used as a negative control. The culture plates were then incubated at 37°C for 24 h. Lastly, the diameter of the inhibition zone on the culture plates was measured as an indicator of the antibacterial capabilities of the coating solutions [17].

The antibacterial properties of the coating solutions were also assessed by determining the microbial growth of *E. coli* and *S. aureus*. Next, 0.1 mL of each coating solution (CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs) was transferred onto a Muller Hinton broth and was incubated at 37˚C in a 100rpm incubator shaker for 24 h. Muller Hinton broth without coating solution was used as blank control. The OD_{600} nm value was measured at 0 h, 2 h, 6 h, 12 h, and 24 h to draw the growth curves. The experiments were repeated in triplicate. The following equation calculated the antibacterial rate:

$$\%\text{inhibition} = (A_0\text{-}A_g)/A_0 \times 100$$

A_0 represents the blank control's OD_{600} nm value, and A_g represents the OD_{600} nm value treated by different coating solutions [19].

2.4 Determination of antifungal properties of the coating solution

The antifungal properties of the coating solutions were determined using the disc diffusion method [20]. Firstly, *F. oxysporum* was cultured in Potato Dextrose Broth at 25°C for 7 days. After that, the culture was filtered using filter paper (11 µm) to obtain the spore solution and remove the residue. The spores in the solution were counted using a haemocytometer. The required spore concentration for the disc diffusion method is 2.5 x 106. Next, 0.1 mL of the spore solution was transferred onto a Potato Dextrose Agar plate and spread evenly using a sterile L-shaped spreader. Subsequently, a single disc (Oxoid, USA) (diameter = 6 mm) was dipped into the coating solution for 10 sec following the concentration respectively and put onto the agar plate. The culture plates were then incubated at 25°C for 7 days. Lastly, the diameter of the inhibition zone that appeared on the culture plates was measured to indicate the antifungal capabilities of the coating solutions [20].

The antifungal properties of the coating solutions were verified in vivo analysis. Bananas were artificially inoculated with *F. oxysporum* by immersing a sterile stainless-steel rod with a probe tip 1 mm wide and 2 mm long into the conidial suspension and wounding each fruit once on the equator. Inoculated bananas were incubated at 28˚C for 24 h. After 24 h, coatings were applied by adding 0.4 mL of the coating material to the banana. Fruits were allowed to air dry at room temperature, placed on trays, and incubated for up to 12 days (Days 0, 6, 9, and 12). During this period, disease incidence (%) was determined by counting the number of decayed fruits (fruits showing visible disease symptoms) and disease severity as the diameter of the lesion (mm) [21].

The bananas were also observed at room temperature for 12 days for a shelf-life study. The physical appearance of bananas was captured using a phone camera, and any changes that occurred were reported [22]. In addition, banana maturity ratings for each fruit were evaluated by comparing the colour of each banana peel with the standard colour chart of bananas [23]. There is a 7-point scale of banana maturity index. 1 = all green, 2 green with trace of yellow, 3 = more green than yellow, 4 = more yellow than green, 5 = yellow with trace of green, 6 = full yellow, 7 = full yellow with brown spots.

2.5 Statistical analysis

The IBM SPSS Software Version 24 (IBM, USA) was used in the study. The data for analysis were expressed as the mean and standard deviation. The mean values were evaluated using the One-way Analysis of Variance (ANOVA) to determine the significant difference ($p<0.05$) between the samples.

3 Results and discussion

3.1 Antibacterial properties of the coating solution

A crucial feature of a coating solution is its antimicrobial properties, including antibacterial and antifungal activities. Antibacterial activity targets the suppression of bacterial growth, the microorganisms that cause spoilage, and foodborne diseases. This attribute is essential for extending the shelf life of food products and ensuring they are safe for consumption. The antibacterial activity of *E. coli* and *S. aureus* was determined using the disc diffusion method and verified by observing the microbial growth of both bacteria using optical density (OD). The use of OD_{600} values to measure microbial growth complements the disc diffusion method in antimicrobial analysis by providing quantitative data that enables a more comprehensive assessment of antimicrobial efficacy.

Fig. 1 presents the antibacterial and antifungal activities of coating solutions containing ZnONPs (CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs) in comparison to the control (CX). The subsequent discussion focuses on the antibacterial activity, while the antifungal activity will be addressed in Section 3.2. The antibacterial activity was assessed by measuring the inhibition zone diameter against *E. coli* and *S. aureus*. Bacteria isolated from the pulp of spoiled ripe plantain fruits, including *Streptococcus sp.* and *Staphylococcus sp.*, are commonly associated with spoilage in *Musa* species [24]. The spoilage of plantain fruits leads to a decrease in quality, resulting in lower market value and financial losses for farmers and traders. In addition, these spoilage bacteria are linked to foodborne illnesses and food poisoning [25]. These pathogens present a significant global public health risk, with *E. coli* causing infections in the gastrointestinal and urinary tracts, while *S. aureus* produces enterotoxins that lead to food poisoning [26].The antibacterial responses towards these two major categories of bacteria can provide a more comprehensive understanding of the CSXG-ZnONPs' inhibitory effects across these two types of bacteria [27].

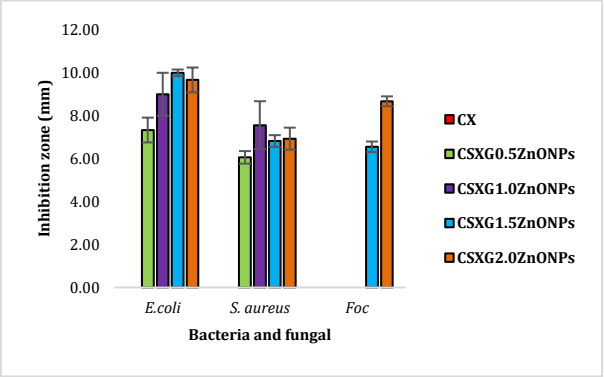

Fig. 1. Antibacterial and antifungal activity of CX, CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs towards *E. coli*, *S. aureus*, and *F. oxysporum*

The study demonstrated that formulations containing zinc oxide nanoparticles (ZnONPs) such as CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs exhibited antibacterial properties by forming inhibition zones against bacteria, unlike the control (CX) which showed no inhibition zone. The CX does not contain ZnONPs as an antibacterial agent and showed no antibacterial properties. The ZnONPs act as an antimicrobial agent triggered by their reaction with water and UV photon energy, producing Zn^{2+} ions. The Zn2+ ions target the negatively charged bacterial cell walls, generating Reactive Oxygen Species (ROS) [28]. The ROS disrupts the cell wall, increases permeability, and causes membrane damage to the bacterial cell [9]. This results in nanoparticle aggregation within the bacterial cells, leading to cell death through cytoplasmic content depletion and respiratory enzyme inactivation [14]. The antimicrobial process also changes the membrane charge and the thickness of bacterial cell walls, and nanoparticles with a higher surface-to-volume ratio can interact more rapidly with the cell wall, enhancing microbial damage [8].

Among the samples containing ZnONPs, no significant ($p>0.05$) inhibition zone of CSXG-0.5ZnONPs compared to the CSXG-1.0ZnONPs and CSXG-1.5ZnOPs and CSXG-2.0ZnONPs shows that it was sufficient at a lower to inhibit the growth of *S. aureus* and *E. coli*. The smallest in particle size and, therefore, the largest in a surface area favourable for its reactivity [9]. Therefore, ZnONPs, increasing the surface-to-volume ratio enhances the antibacterial effect [29]. The results obtained approximated the findings by Sarbon *et al*. [9]; the lack of significant results at 1.5% and 2% concentrations was caused by an uneven distribution of ZnONPs within the coating solution at higher concentrations. The clumping blocks ZnONPs, which are responsible for the antimicrobial activity, resulting in reduced effectiveness [12]. Santosh *et al.* [28] also reported similar findings for ZnONPs at 3% and 5% concentrations. The effective interaction between active molecules and the polymeric matrices of the coating solution may slow diffusion through adjacent agar media, reducing contact between bacterial cells and active molecules.

La *et al.* [27] showed that ZnONPs exhibited good antibacterial properties against several bacteria, including *S. aureus* and *E. coli*. The ZnONPs as an antibacterial agent were incorporated into chitosan and gum arabic coating, and the protective performance for the banana preservation was successfully conducted. A study by Helmiyanti *et al.* [30] also shows that the CMC/PVA film did not show antibacterial activity, while films incorporated with ZnONPs exhibited antibacterial activity against *E. coli* and *S. aureus*. Fig. 1 also reported the antifungal activity towards *F. oxysporum*. The results are discussed in Section 3.2.

Fig. 2 illustrates the microbial growth of *E. coli* at different time points: 0, 2, 6, 12, and 24 h of incubation. All samples began with an OD_{600} value of 0.011 at 0 h. By 2 h, the OD_{600} values for all samples increased, indicating an increase in microbial growth, and this trend continued up to 6 h. Notably, the OD_{600} for the CSXG-1.0ZnONPs sample remained significantly lower than the others throughout the 24 h. At 24 h, the OD_{600} values for CX, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs increased steadily, whereas the CSXG-0.5ZnONPs and CSXG-1.0ZnONPs samples showed a slower rate of increase. Overall, the CSXG-1.0ZnONPs sample consistently maintained the lowest OD value compared to the other samples throughout the incubation period, indicating the least microbial growth.

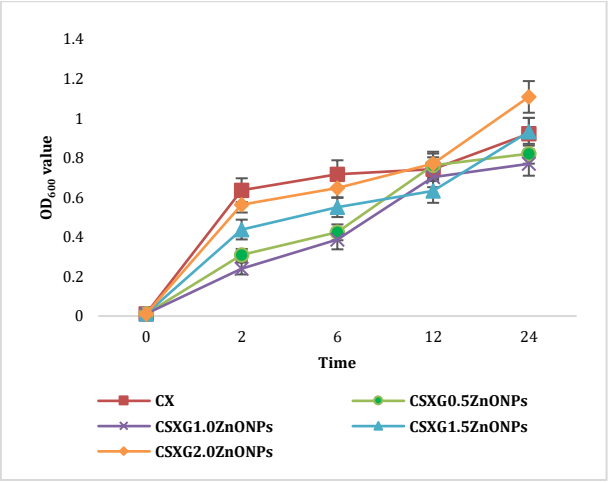

Fig. 2. Microbial growth of *E. coli* for CX, CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs

The trend is the same for the microbial growth of *S. aureus*, as shown in Fig. 3. Fig. 3 illustrates the microbial growth of *S. aureus* at different time points: 0, 2, 6, 12, and 24 h incubation. All samples began with an OD_{600} value close to zero at 0 h. By 2 h, the OD_{600} values for all samples increased, indicating an increase in microbial growth, and this trend continued up to 6 h. By 24 h, the CX, CSXG0.5ZnONPs, and CSXG2.0ZnONPs samples showed a continued steady increase in OD_{600} values, reflecting sustained microbial growth. In contrast, CSXG1.0ZnONPs showed a slower increase, and CSXG1.5ZnONPs exhibited moderate growth. Overall, the CSXG1.0ZnONPs sample consistently maintained the lowest OD value compared to the other samples throughout the incubation period, indicating the least microbial growth.

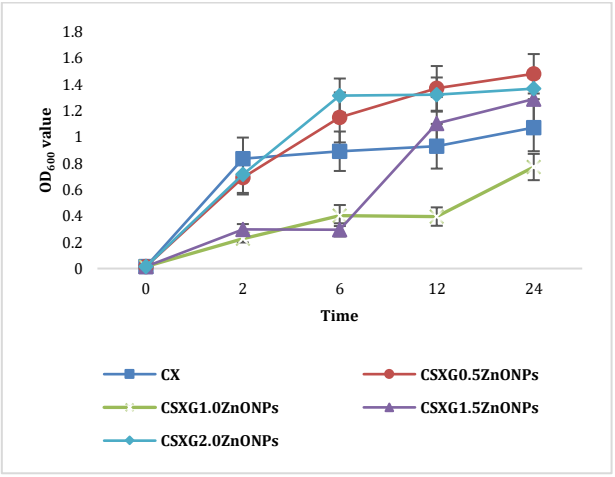

Fig. 3. Microbial growth of *S. aureus* for CX, CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs

Fig. 4 shows the antibacterial rate of *E. coli* and *S. aureus*. The graph shows that CSXG1.0ZnONPs shows the highest antibacterial rate. The larger inhibition zone observed for *S. aureus* compared to *E. coli* is consistent with the findings of Silva *et al.* [31]. *S. aureus*, a gram-positive bacterium, has a thick peptidoglycan layer made up of repeated units of carbohydrates and amino acids, which enhances its interaction with ZnONPs. In contrast, *E. coli*, a gram-negative bacterium, has a thinner peptidoglycan layer and an outer membrane containing lipopolysaccharides that reduce the antibacterial effectiveness of ZnONPs [31]. Gram-positive bacteria are generally more susceptible to ZnONPs because they lack the protective outer membrane found in gram-negative bacteria, which provides more excellent resistance. The complex cell wall structure of gram-negative bacteria like *E. coli* can interfere with the attachment and activity of nanoparticles [28]. Additionally, due to differences in cell membrane polarity, *E. coli* exhibits more excellent resistance than *S. aureus*. *S. aureus* has a less negative charge that allows oxidising free radicals to penetrate more efficiently, ultimately leading to cell death [32].

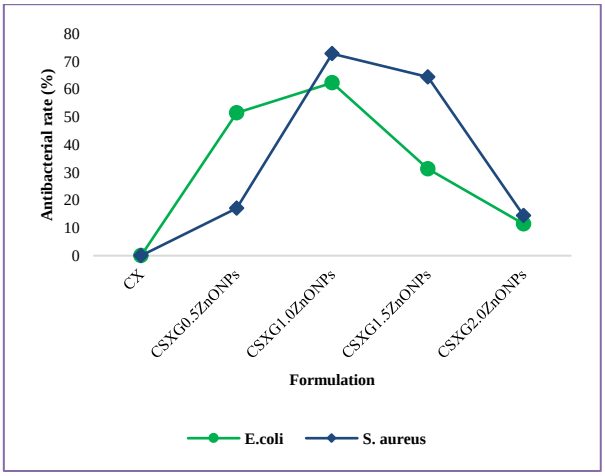

Fig. 4. Antibacterial rate of *E. coli* and *S. aureus* for CX, CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs

There is also research reported that *E. coli* shows a higher inhibition. The inhibition due to the differential sensitivity can be attributed to the unique cell wall structures of Gram-negative and Gram-positive bacteria. Gram-negative bacteria have a thin peptidoglycan layer sandwiched between two membranes and possess dissociated carboxyl groups that generate negative charges on the cell surface, making them more susceptible to the positive charge of ZnONPs (+24 mV zeta potential). The electrostatic attraction between the negatively charged bacterial cell surface and the positively charged ZnONPs facilitates more effective penetration and disruption of the cell membrane in Gram-negative bacteria. This mechanism leads to significant cell damage at lower nanoparticle concentrations, suggesting a more inhibition of *E. coli* compared to *S. aureus* [33].

3.2 Antifungal properties of the coating solution

The antifungal activity involves preventing the growth of fungi, including moulds and yeasts, which can also lead to spoilage and reduce the quality of food products. An effective coating with antifungal properties can help maintain the freshness and safety of food by creating a barrier that inhibits microbial growth. *Fusarium oxysporum*, a major agricultural pest responsible for *Fusarium* wilt, affects crucial crops worldwide. Its ability to survive in soil, widespread prevalence, and growing resistance to conventional fungicides highlight the urgent need for antifungal approaches [34]. The *Fusarium oxysporum* used in this study is *Fusarium oxysporum fs cubense* due to the availability of this pure culture. This form of *Fusarium oxysporum* is known for causing a serious disease in bananas called Panama disease or banana wilt. The pathogen spreads through contaminated soil, water, and plant debris (Anusha et al., 2024).

Fig. 1 also shows the antifungal activity of coating solutions containing ZnONPs (CSXG-0.5ZnONPs, CSXG-1.0ZnONPs, CSXG-1.5ZnONPs, and CSXG-2.0ZnONPs) compared to the control (CX). The CX showed no inhibition zone because it does not contain ZnONPs as an antifungal agent and does not show antimicrobial properties. The study revealed that CSXG-1.5ZnONPs and CSXG-2.0ZnONPs demonstrated antifungal activity against *F. oxysporum* by creating inhibition zones. According to research by Abdelaziz *et al.* [35], hydrogels infused with ZnONPs effectively inhibited the growth of *Fusarium oxysporum*, primarily by causing deformation of the fungus's mycelium. This structural disruption likely contributes to the observed growth inhibition. Additionally, ZnONPs inhibited the synthesis of mycotoxins and promoted the transcription of genes linked to antioxidant capacities. This suggests that ZnONPs attack the fungal structure, disrupt cellular processes, and trigger oxidative stress, potentially enhancing the host's defence response by activating antioxidant enzymes.

A study by Wardana *et al.* [36] also demonstrated that combining chitosan, zinc oxide nanoparticles, and sandalwood essential oil effectively controlled the growth of *Penicillium italicum*, showing significant inhibition of spore germination and mycelial growth compared to the control. The study also noted that the interaction between the nanoparticles and microbes was less effective in solid media than in liquid media [37].

Formulation/ Day	**0**	**6**	**9**	**12**
CX (Control)				

Fig. 5. In-vivo antifungal and shelf-life analysis of coated bananas

An in vivo analysis was done to verify the coating solution's antifungal activity by infecting the banana with *F. oxysporum*. From Fig. 5, the *F. oxysporum* does not infect the peel from the hole at the centre of the banana peel; direct signs of infection cannot be seen on the outer skin. *F. oxysporum* targets the internal vascular system of bananas rather than the peel, which is not pathogenic to the peel of bananas. *F. oxysporum* began in internal tissues where artificially infected tests for antifungal coatings did not significantly affect the peel. For several decades, bananas have been affected and devastated by the Fusarium wilt of bananas. The soil-borne Fusarium causes the disease *F. oxysporum*, which colonises the vascular system of the banana plant, causing wilting, chlorosis of leaves, and finally, the death of the infected plant [38].

Despite no inhibition of fungal growth on the peel, the study revealed that the coated bananas exhibited an extended shelf life. The shelf-life of bananas refers to the duration the fruit can maintain its quality from the initial ripening stage until it becomes inedible. The ripening stage of bananas refers to the period when the fruit transitions from a green, unripe state to a yellow, ripe state, marked by the development of sweetness and softening. This stage is critical as it affects the fruit's texture, flavour, and overall quality before it begins to deteriorate. As shown in Fig. 5, by day 6, bananas coated with CX reached the maturity index 6 (full yellow) compared to CSXG-0.5ZnONPs and CSXG-1.0ZnONPs reached maturity index 3 (more green than yellow), while those coated with CSXG-1.5ZnONPs and CSXG-2.0ZnONPs progressed to index 5 (yellow with trace of green). By day 9, the CX reached maturity index 7 (fully yellow with brown spots) compared to CSXG-0.5ZnONPs and CSXG-1.0ZnONPs bananas reached maturity index 4 (more yellow than green), while CSXGS-1.5ZnONPs and CSXG-2.0ZnONPs progressed to index 6 (full yellow). By day 12, the CX reached maturity index >7 (more brown spots than yellow) compared to CSXG-0.5ZnONPs and CSXG-1.0ZnONPs bananas reached index 6 (full yellow), whereas the CSXG-1.5ZnONPs and CSXG-2.0ZnONPs bananas exhibited bruising and eventually advancing to index 7 (full yellow with brown spots). These results align with the findings of Thakur et al. (2018), who developed a rice starch coating with sucrose ester to manage postharvest ripening and extend the shelf life of Cavendish bananas [39].

4 Conclusion

This study highlights the effectiveness of an innovative coating solution comprising cassava starch, xanthan gum, and ZnONPs in extending the shelf life of bananas. The in vitro antibacterial testing, using the disc diffusion and microbial growth using OD_{600} value, demonstrated that a 1% ZnONPs significantly ($p<0.05$) inhibited *E. coli* and *S. aureus* growth. Meanwhile, a 2% concentration was significant ($p<0.05$) in inhibiting *F. oxysporum*. The in vivo tests showed no *F. oxysporum* growth, which does not affect the banana peel. Overall, the shelf-life assessment showed that coated bananas had an extended shelf life. These findings reveal the potential of using a composite of cassava starch for protection, ZnONPs for their antimicrobial properties, and xanthan gum to enhance adhesion. This not only meets local market demands but also may support export opportunities by preserving the quality and safety of bananas during storage and transportation.

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