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Original Article

Effect of Nano-Encapsulated Edible Aloe Vera Gel Coating Enriched with *Ziziphora tenuior* Essential Oil on Postharvest Quality of *Citrus sinensis*

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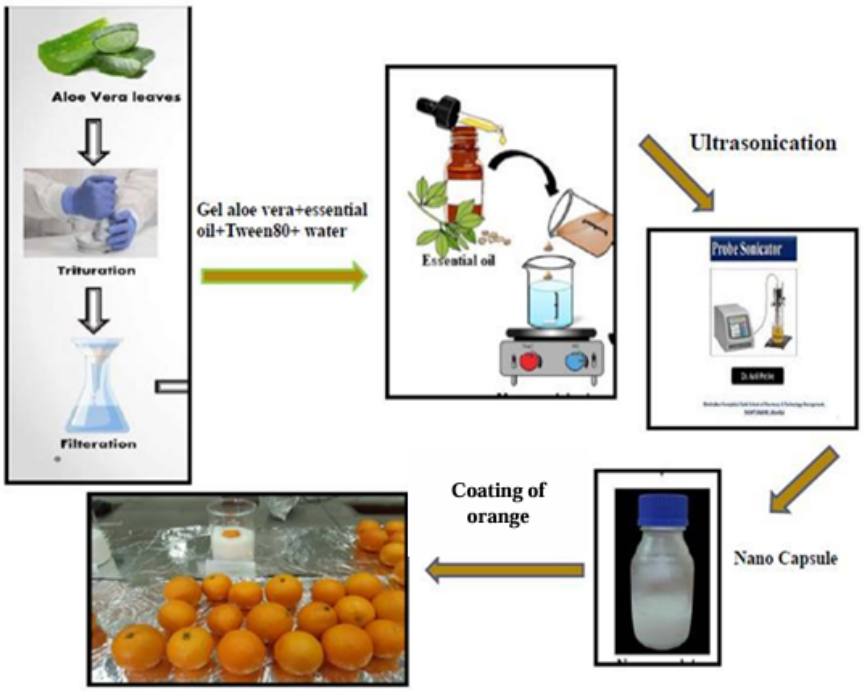
ABSTRACT

This study investigated the potential of Aloe vera gel nanocapsules loaded with *Ziziphora tenuior* essential oil to enhance the shelf life and quality of Valencia oranges by controlling *Penicillium digitatum*. Analysis of the essential oil identified 21 bioactive compounds, and in vitro assays revealed a concentration-dependent inhibition of *P. digitatum* mycelial growth, reaching approximately 90% inhibition at 3 ml/L. Nanocapsules synthesized with an average particle size of 75 nm and a zeta potential of -16 mV were applied as coatings on oranges. Over a 60-day storage period, the nanocapsule treatment effectively minimized weight loss to 1.5%, outperforming Aloe vera gel (3.1%) and essential oil alone (3.9%). Fruit firmness was better preserved with treatments containing nanocapsules, aloe gel, and essential oil. At the same time, nanocapsules also limited the increase in soluble solids content (SSC) from 9.4% to 10.6%, compared to a rise up to 13.8% in the control. Moreover, the nanocapsule coating maintained a relatively stable titratable acidity (TA) between 30 and 60 days (0.95 to 0.84 g citric acid/L). These findings demonstrate that nanoencapsulation of *Z. tenuior* essential oil in Aloe vera gel significantly enhances its antifungal activity and fruit preservation properties, offering an effective postharvest strategy to extend the shelf life and maintain the quality of citrus fruits.

Keywords: Valencia orange, *Penicillium digitatum*, Postharvest, Antifungal, Vitamin C



INTRODUCTION

Postharvest decay caused by *Penicillium digitatum* remains a significant challenge in citrus preservation, accounting for approximately 90% of global production losses despite the extensive use of fungicides and biological control methods [1, 2]. This pathogen reduces fruit quality during packing, transportation, and marketing, leading to substantial economic losses [3, 4]. Considering the global nutritional and economic importance of citrus fruits—primarily due to their high vitamin C content, a key antioxidant vital for maintaining fruit quality—preserving their postharvest integrity is essential [5, 6]. Maintaining vitamin C levels during storage is critical to preserving both sensory

and nutritional attributes [6]; however, citrus fruits are highly perishable with a typical shelf life of only 5 to 7 months postharvest [7]. Conventional preservation methods such as cold storage and wax coatings can extend freshness to a degree, yet they have limitations in preventing microbial decay and moisture loss [8, 9]. Essential oils (EOs) have attracted significant attention as natural, safe alternatives to synthetic fungicides because of their antimicrobial and antifungal properties [10, 11, 12]. EOs derived from *Mentha arvensis*, basil (*Ocimum canum*), ginger (*Zingiber officinale*), thyme (*Thymus vulgaris*), and cinnamon (*Cinnamomum zeylanicum*) have shown effectiveness against *Penicillium* species on citrus fruits [13]. However, the practical use of essential oils is hindered by their volatility and chemical instability. Environmental factors such as heat, humidity, light, and oxygen cause rapid degradation of EOs, reducing their antimicrobial efficacy and limiting sustained activity on fruit surfaces [14]. Nanoencapsulation provides a powerful solution by entrapping essential oils within nanostructured carriers, physically protecting EO molecules from environmental degradation and enabling controlled release [14,15]. This Technique increases the water solubility and bioavailability of hydrophobic EO components, thereby improving their interaction with microbial cells. Most importantly, nanoencapsulation offers a controlled and sustained release of bioactive compounds, maintaining effective antimicrobial concentrations over extended periods. This sustained release reduces the total EO dosage required, minimizing adverse sensory effects such as off-flavors, while prolonging antimicrobial activity [16, 17]. Numerous studies report that nanoencapsulated essential oils exhibit higher antifungal efficacy compared to their free counterparts, as demonstrated with nanoencapsulated thyme and oregano oils against postharvest pathogens [18]. Thus, nanoencapsulation represents a novel, efficient strategy to enhance the stability and functional performance of essential oils for citrus postharvest preservation.

Aloe vera gel is widely acknowledged not only for its biocompatibility but also for its intrinsic antimicrobial, antioxidant, and film-forming properties, making it an excellent natural matrix for encapsulation and edible coatings [19, 20,]. With over 99% water content, Aloe vera gel forms semi-permeable films that regulate gas and moisture exchange, thereby reducing fruit respiration rates and moisture loss. Natural antioxidants present in Aloe vera help scavenge reactive oxygen species, protecting fruits from oxidative spoilage and maintaining quality. Additionally, bioactive compounds such as anthraquinones and polysaccharides contribute to its antimicrobial capacity, enhancing the protective effect of encapsulated essential oils [21]. Studies have also demonstrated that Aloe vera gel improves the solubility, environmental stability (against light and heat), and bioavailability of bioactive compounds like curcumin through encapsulation [22]. Taken together, Aloe vera offers multifunctional benefits far beyond simple biocompatibility, providing both physical barrier properties and bioactive protection [22].

While nanoencapsulation ensures controlled delivery and improved bioavailability of essential oils, edible coatings contribute complementary mechanisms by forming a physical barrier over the fruit surface that reduces moisture loss, delays respiration, and limits microbial infiltration [23]. Edible coatings are typically composed of natural biopolymers such as polysaccharides, proteins, and lipids, which provide mechanical strength and barrier properties. Incorporating nanoencapsulated essential oils within these coatings creates a synergistic effect: the coating retains the nano carriers in close contact with the fruit surface, optimizing localized antimicrobial compound delivery. This combination enhances coating stability and barrier function while enabling sustained release of active agents, resulting in an integrated, more effective preservation system. The novelty of this study lies in the integrated application of nanoencapsulated *Z. tenuior* essential oil within an Aloe vera-based edible coating for Valencia orange preservation. Although prior studies have separately investigated essential oils, edible coatings, and nanoencapsulation, the combined use of *Z. tenuior* EO nanoencapsulated in Aloe vera gel coatings has not been thoroughly explored in citrus preservation. This approach uniquely marries the potent antifungal activity of *Z. tenuior* oil, the film-forming and bioactive properties of Aloe vera, and the benefits of nanoencapsulation-driven controlled release. This research evaluates key postharvest quality parameters directly affecting fruit freshness, nutritional value, and marketability. Compared to conventional fungicides or individual use of edible coatings or essential oils, this combined nanoencapsulated coating system offers several advantages: Improved antifungal efficacy against *P. digitatum* through sustained and controlled EO release, Potential reduction in synthetic fungicide use, promoting safer and more sustainable postharvest management, Extended shelf life and decreased weight loss due to synergistic physical barriers and bioactive antimicrobial action, Better retention of fruit firmness, flavor, and antioxidant content, enhancing overall quality and consumer acceptance, Minimization of adverse sensory effects due to lower essential oil dosages [24, 25], Hence, this integrated and innovative approach provides a natural, safe, and sustainable alternative for optimal postharvest citrus preservation, reducing economic losses and supporting the citrus industry's long-term sustainability.

MATERIAL AND METHODS

Preparation of *Z. tenuior* Essential Oil and Aloe-Gel

Z. tenuior essential oil was provided by Barij Essence Pharmaceutical Company, located in Kashan, Iran. The components of the essential oil were subsequently identified and quantified using gas chromatography-mass spectrometry (GC-MS) [26]. GC-MS analysis was performed using a Thermoquest-Finnigan gas chromatograph equipped similarly to the GC system described above, coupled with a TRACE mass spectrometer (Manchester, UK). Helium was used as the carrier gas, and the ionization voltage was set at 70 eV. The ion source and interface temperatures were maintained at 200 °C and 250 °C, respectively. The mass range scanned was from 35 to 456 amu. The oven temperature program was the same as that used in the GC analysis.

Fresh Aloe vera gel was prepared following established protocols outlined in previous studies [24]. The Aloe vera rind was washed thoroughly to remove impurities. Mature leaves of the Aloe vera plant were collected, and the thick outer skin was carefully removed. The gel was then rinsed with warm water to eliminate the yellow sap. The pulp was homogenized with an electric blender and filtered to remove any remaining impurities.

Antifungal Activity of *Z. tenuior* Essential Oil

The antifungal effect of *Z. tenuior* essential oil was investigated by incorporating it into Potato Dextrose Agar (PDA) media, which was prepared from 200 g/L potato extract, 20 g/L dextrose, and 15 g/L agar (HiMedia, India), at concentrations of 0, 1.5, 2, 2.5, and 3 ml/L. *P. digitatum* spores were harvested from 7-day-old cultures grown on PDA plates. The spores were collected by gently flooding the surface

of the culture with sterile distilled water containing 0.05% Tween 80, then gently scraping with a sterile loop to release the spores. The spore suspension was filtered through sterile cheesecloth to remove mycelial fragments, and the concentration was adjusted to 10^6 spores/mL using a hemocytometer. The *P. digitatum* culture was originally obtained from the fungal culture collection of the Center for Agricultural Research and Education of Khorasan Razavi, Iran. Subsequently, 10 microliters of this spore suspension (10^6 spores/mL) were inoculated at the center of the plates. The plates were incubated at 28°C for 10 days in the dark, with relative humidity maintained at approximately 90%. The antifungal activity was evaluated by measuring the diameter of fungal colony growth on the PDA plates compared to the control (without essential oil). The inhibition of fungal growth was calculated based on the reduction in colony diameter, providing a quantitative measure of the antifungal effect of the *Z. tenuior* essential oil [27].

Preparation of Nanocapsule Formulation using Aloe Gel.

The nanocapsules were prepared using essential oil, Aloe vera gel, and Tween 80 at weight percentages (w/w) of 3%, 50%, and 2%, respectively. These proportions were calculated based on the total weight of the formulation to ensure accuracy and reproducibility. First, the essential oil and Tween 80 (Tween 80 used: Merck, Germany, Industrial Grade) were weighed separately and then mixed using a vortex mixer at 2000 rpm for 2 minutes to form a primary emulsion. Subsequently, Aloe vera gel and distilled water were gradually added to the mixture. The entire formulation was then stirred with a magnetic stirrer (Thermo Scientific Cimarec+ digital model) at 500 rpm for 15 minutes to obtain a homogeneous solution. For the ultrasonication step, the sample was processed with a Hielscher UP 400S ultrasonic probe operating at a frequency of 24 kHz and 400 watts' power. The sonication was applied in pulse mode with 30-second ON and 15-second OFF intervals for a total processing time of 10 minutes. To prevent temperature, rise and maintain the stability of the nano capsules, the sample was kept in an ice bath during ultrasonication, maintaining the temperature between 20 °C and 25 °C [28].

Analyzing the Properties of Nano Capsules

The characteristics of the nanocapsules were evaluated by measuring the mean particle size diameter, polydispersity index (PDI), and Zeta potential using a particle size analyzer (DLS) (Zeta Sizer Nano-ZS; Malvern Instruments Ltd., United Kingdom). For the DLS measurements, the refractive index and viscosity of the dispersant medium were set at 1.33 and 0.89 cP, respectively. In addition, transmission electron microscopy (TEM) was utilized to examine the morphology of the nanocapsules through microscopic imaging (TEM; CEM 902A; Zeiss, Oberkochen, Germany) [29].

Experimental Design and Treatment Details

Valencia oranges harvested from the orchards of Sari city, Mazandaran province, Iran, were selected for uniform maturity based on a standardized color index indicating optimal ripeness and with a size range of 75–85 mm in diameter. Only fruits free from external blemishes and mechanical damage were used. For surface sterilization, the oranges were immersed in a 0.25% (w/v) sodium hypochlorite solution diluted in distilled water for 2 minutes to ensure effective disinfection without harming the fruit. The *P. digitatum* spore suspension was prepared by harvesting spores from 7-day-old cultures grown on potato dextrose agar plates. Spores were suspended in sterile distilled water containing 0.01% Tween 80 to prevent clumping, and the spore concentration was standardized to 1×10^6 spores/mL using a hemocytometer [27]. A 3 mm deep incision was made in the skin of each orange, and 20 microliters of the spore suspension were introduced into these wounds using a sampler. Six hours after inoculation, the fruits were subjected to a 90-second treatment by dipping the entire surface of each fruit into one of the test solutions: nanocapsules of Aloe vera gel containing essential oil, Aloe vera gel containing essential oil, essential oil emulsion, or distilled water as a procedural control. Additionally, a negative control group with no *P. digitatum* inoculation and no treatment was included. The treated and control fruits were then packed in small plastic baskets, each containing three fruits, and stored in a dark cold storage chamber maintained at 5°C and 80% relative humidity with continuous gentle air circulation for a duration of 60 days.

Physicochemical Analysis

Physicochemical analysis of Valencia oranges was conducted fifteen days after coating treatments and repeated every 15 days in four intervals. For sample preparation, 30 g of oranges from each treatment group were peeled, cut into small pieces, and blended using a digital blender until homogeneous. Total acidity (TA) was determined by titrating the orange juice with 0.1 N sodium hydroxide to a phenolphthalein endpoint, as described in the AOAC official method, and expressed as grams of citric acid equivalent per 100 g of orange. pH was measured directly on the homogenized juice using a calibrated pH meter. Soluble solids content (SSC) was measured with a digital refractometer based on the AOAC procedure by placing a drop of juice on the prism surface and recording the °Brix value. For firmness assessment, a digital penetrometer equipped with an 8 mm diameter cylindrical probe was used; penetration was performed at a speed of 5 mm/s on two opposite sides of each fruit. Vitamin C content (mg/100 g) was quantified using the 2,6-dichlorophenol-indophenol visual titration method following the protocol described by Rangana [30]. For all physicochemical tests, three samples per treatment were analyzed at each sampling time. Weight loss was monitored at 15-day intervals using a digital scale, and results were expressed as a relative percentage compared to initial weight.

Measurement of Fruit Decay (Mildew)

The decay rate and the number of rotten fruits were evaluated using a scoring method. The scores were assigned as follows: 5 for healthy fruits with no decay, 4 for partial decay affecting less than 5% of the fruit surface, 3 for low decay covering 5–10%, 2 for moderate decay affecting 10–15%, and 1 for high decay covering 15–20% or more of the fruit surface, indicating significant adverse changes. To improve reproducibility and objectivity, a visual scale with representative photographs illustrating each score level was prepared and used during evaluation. Additionally, all observers underwent prior training and calibration sessions to minimize subjective bias and ensure consistency in decay scoring.

Data Processing and Analysis

The experiment employed a factorial design using a completely randomized design (CRD) with three replicates. Data from all assays were analyzed using one-way analysis of variance (ANOVA) followed by the Tukey Honestly Significant Differences (HSD) Post-Hoc test, utilizing Minitab software version 16. Graphs were generated using GraphPad Prism version 9 for Windows (GraphPad Software, California, USA).

RESULTS AND DISCUSSION

Table 1 Chemical Composition of Essential Oil of *Ziziphora tenuior* L.

No	Components	Quantity (%)	Retention Time (RT, min)
1	α-Pinen	1.0	6.51
2	Camphene	0.2	7.03
3	β-Phellandrene	0.6	7.73
4	ß-Pinene	1.2	7.92
5	ß-Myrcene	0.3	8.24
6	3-Octanol	0.3	8.54
7	o-Cymene	0.2	9.59
8	Limonene	1.0	9.73
9	1,8-Cineole	6.01	9.89
10	α-Campholenol	3.3	14.78
11	1-Menthone	0.6	15.09
12	Menthofuran	12.72	15.37
13	1-Menthone	0.8	15.49
14	Isoborneol	0.3	15.75
15	cis-Dihydrocarvone	1.5	15.99
16	α-Terpineol	0.2	16.80
17	Pulegone	65.23	18.83
18	Thymol	0.8	21.36
19	α-Naginatene or Rosefuran	0.7	23.16
20	Caryophyllene	0.6	26.37
21	Cycloionone	1.5	51.82
	Total	99.06	

Properties of Nanocapsules

The results obtained from transmission electron microscopy (TEM) images revealed that the initial size of the synthesized nanocapsules was 75 nm. Over time, an increase in size was observed in the nanocapsules, while maintaining a spherical shape (Fig. 1a, b). The nanocapsules maintained a spherical shape over time (Fig. 1a, b). The sphericity of nanocapsules is known to enhance the stability and preservation of encapsulated essential oils by minimizing surface area exposure to the external environment, thus reducing oxidation and volatilization losses. Moreover, spherical particles exhibit more uniform surface energy distribution, which helps to form a more stable barrier around the core material [31]. Several studies have demonstrated that spherical morphology contributes to improved encapsulation efficiency and sustained release profiles of essential oils, ultimately protecting their bioactive compounds during storage [31, 32].

The average particle size diameter, polydispersity index (PDI), and zeta potential of Aloe-gel nanocapsules containing *Z. tenuifolia* essential oil were monitored over a period of 60 days. The PDI of the nanocapsules increased by approximately 10% after 60 days (Fig. 1b). This increase in polydispersity was mainly correlated with a decrease in the absolute value of the zeta potential—from an initial value of approximately -15 mV—over the same period (Fig. 1B, C). A decrease in the absolute zeta potential reduces the electrostatic repulsion forces between particles, which can promote aggregation and, consequently, an increase in the average particle size. It is generally accepted that zeta potential values between ±15 mV indicate moderate stability, and values closer to zero suggest a tendency for aggregation. In our formulation, the measured zeta potential around -15 mV implies borderline colloidal stability. This was supported by visual observations (e.g., slight turbidity increase) and an increase in particle size over time, suggesting some degree of aggregation. However, no significant sedimentation was observed during the monitoring period. The coating of the nanocapsules by non-ionic surfactant components is believed to contribute to steric stabilization, complementing the electrostatic effects and partially limiting instability.

Further quantitative correlation between zeta potential decrease and aggregation was confirmed by the gradual increase in PDI and hydrodynamic size, indicating decreased colloidal stability over time [33].

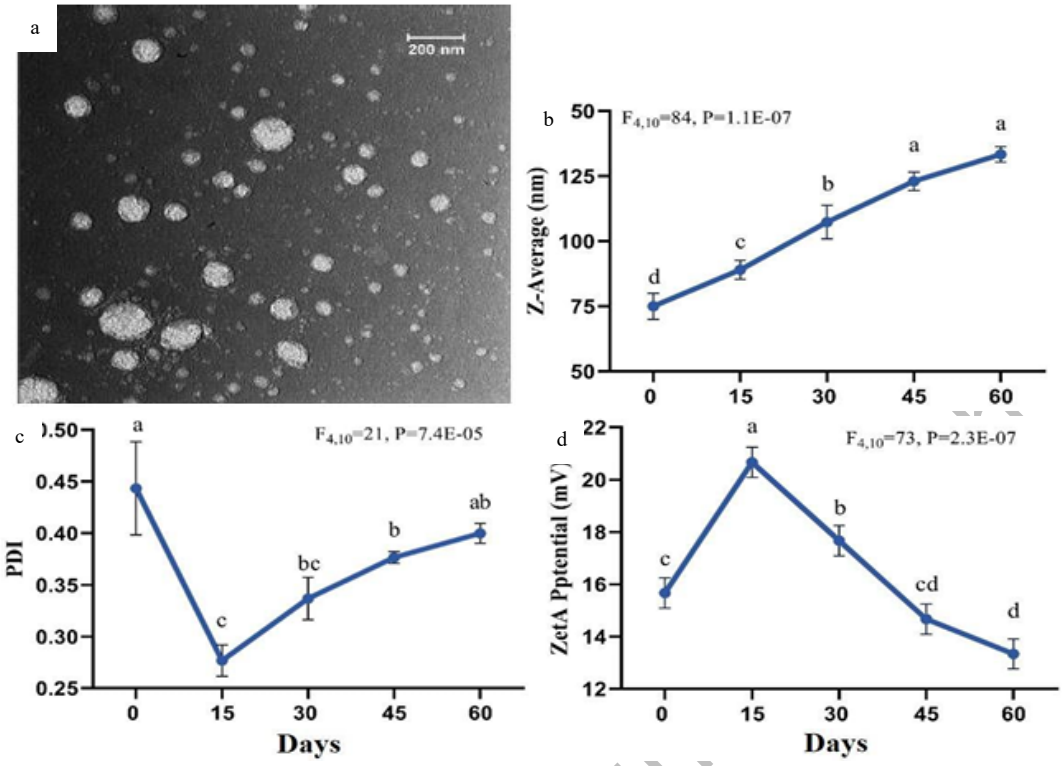
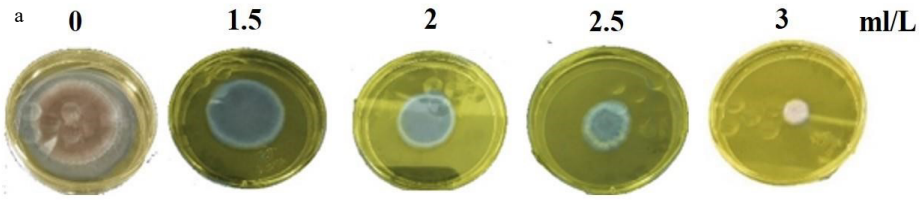


Fig. 1 The TEM electron microscope image depicts the nanocapsules of *Aloe vera* gel containing *Z. tenuior* L. essential oil (a), Z-average diameter (Z-average) (b), the polydispersity index (c), and the Zeta potential (d) of the nanocapsules for 60 days post-preparation. The data represent the mean values of three replicates. Error bars indicate the standard deviation of the mean (SD). Statistical comparisons between different treatments at each individual time point were performed using one-way ANOVA followed by Tukey's post hoc test with a significance level of $p \leq 0.05$, where different letters denote significant differences.

The Impact of *Z. tenuior* Essential Oil on Inhibition of *P. digitatum*

To examine the inhibitory effect of *Z. tenuior* essential oil on the pathogenic fungus *P. digitatum*, essential oil concentrations of 0, 1.5, 2, 2.5, and 3 ml/L were incorporated into PDA media. The mycelial growth of *P. digitatum* decreased with increasing concentrations of the essential oil (Fig. 2a). At 3 ml/L, the essential oil achieved approximately 90% inhibition of fungal growth (Fig. 2b). This level of inhibition is comparable to, or in some cases exceeds, the efficacy reported for commonly used synthetic fungicides such as thiabendazole and imazalil against *P. digitatum* [34], highlighting the potential of *Z. tenuior* essential oil as a natural antifungal agent. Previous research has demonstrated that *Z. tenuior* essential oil possesses potent antioxidant, antibacterial, antifungal, and antiviral activities. Key bioactive constituents identified in this essential oil—such as pulegone, menthofuran, and 1,8-cineole—have documented antifungal properties. For example, pulegone has been shown to disrupt fungal cell membranes, causing electrolyte leakage, which leads to depletion of intracellular amino acids and sugars, ultimately inhibiting fungal growth [35]. Similarly, menthofuran and 1,8-cineole contribute to antifungal effects through membrane destabilization and interference with cellular metabolism [36]. The proposed antifungal mechanism against *P. digitatum* involves the reduction of spore germination and mycelial development, primarily due to the combined activity of these bioactive compounds. This multifaceted mode of action not only inhibits fungal growth but may also reduce the likelihood of resistance development [37].



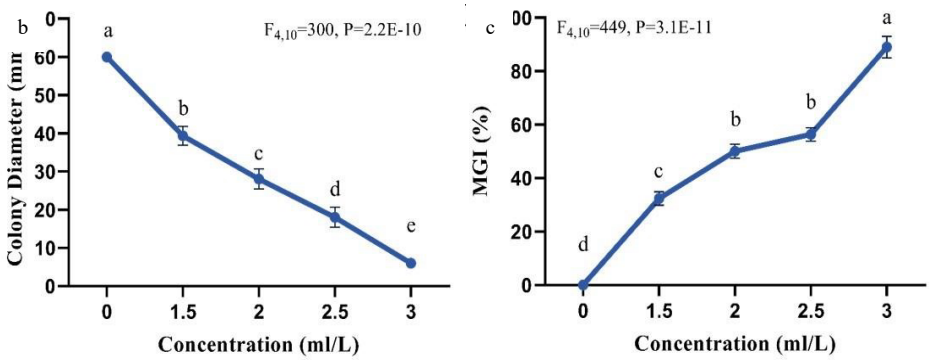


Fig. 2 Evaluation of the antifungal activity of *Z. tenuior* L. essential oil at concentrations of 0, 1.5, 2, 2.5, and 3 ml/L. (a) Representative images of fungal colonies. (b) Colony diameter (mm). (c) Mycelial Growth Inhibition (MGI, %) expressed as percent inhibition relative to the untreated control. Data represent the mean values of three replicates. Statistical significance was determined using Tukey's test at $p \leq 0.05$. Different letters indicate significant differences. Error bars represent the standard deviation (SD) of the mean.

The Effect of Nanocapsule of Aloe Vera Gel with Essential Oil on Post-Harvest Parameters

Fruit weight loss plays a pivotal role in determining fruit quality, primarily attributed to water loss caused by respiration [38]. At the start of storage (day 0), no weight loss is observed. Over time, all treatments show an increase in weight loss due to respiration and water loss. After 15 days, the nanoemulsion treatment exhibits the least weight loss (approximately 0.3%), followed by Aloe vera gel (1%) and Essential oil (1.3%), while the Control shows the highest weight loss (1.6%). By 60 days, the nanoemulsion treatment continues to minimize weight loss most effectively, with a loss of 1.5%. Aloe vera gel and Essential oil treatments have significantly higher weight losses of 3.1% and 3.9%, respectively. Results of statistical analysis showing significant differences among the treatments ($p < 0.01$). Specifically, the nanemulsion treatment has a statistically lower weight loss compared to Aloe vera gel and Essential oil (Fig. ٣a). Overall, the data demonstrate that the nanoemulsion treatment is the most effective at preserving fruit weight during storage, which is an important factor in maintaining fruit quality. These findings indicate that while nanocapsules maintained stability over 60 days, Aloe vera and essential oil treatments lost effectiveness due to decomposition. Differences in weight loss among the edible coatings may also be influenced by variations in coating thickness and rheological properties, however, data on these factors were not evaluated in this study and could be considered for future research. Coating techniques establish a protective barrier on fruit surfaces, reducing moisture loss and preserving freshness and quality, which is crucial for extending shelf life and maintaining market value. The use of nanocapsules and Aloe vera gel has been reported not to affect the taste, aroma, and texture of fruits [39].

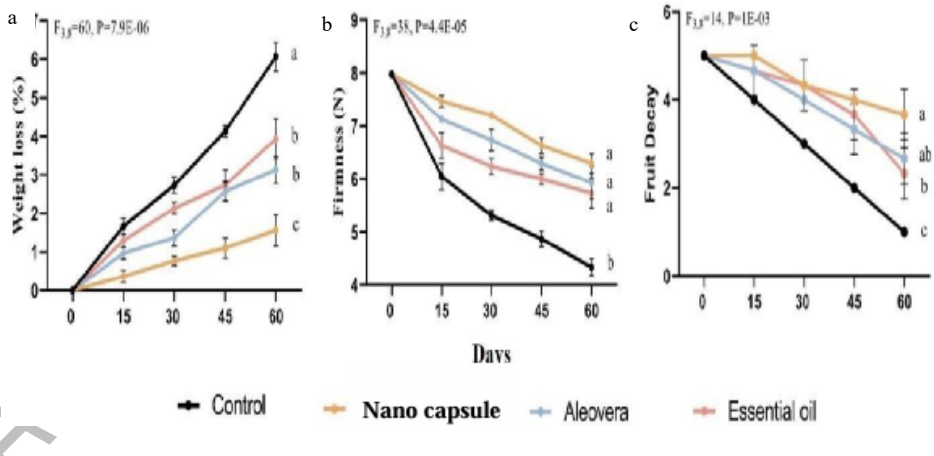


Fig. 3 Effect of nanocapsule treatment on marketability indices of Valencia oranges during storage. (a) Weight loss (%), (b) Firmness (N), and (c) Fruit decay incidence (%). Oranges were stored at 5 °C and relative humidity of 80 ± 5% for 60 days. Treatments included control (no treatment), nanocapsule containing essential oil, Aloe vera gel, and essential oil. Data represent the mean values of 3 oranges per treatment. Error bars indicate the standard deviation (SD) of the mean. Statistical analysis was performed using one-way ANOVA followed by Tukey's multiple comparison test ($p \leq 0.05$). Different letters indicate statistically significant differences among treatments.

Firmness, color, and aroma are crucial attributes that consumers prioritize when selecting certain types of fruit [40]. During storage, fruit firmness declined, with the control group of fruits softening at a faster rate compared to those treated with nanocapsules, Aloe vera, and essential oils (Fig. 3b). Over 60 days, the firmness of oranges coated solely with an edible coating plummeted from 8 N to 4 N for the control group (Fig. 3b). This softening mainly results from the action of hydrolytic enzymes on carbohydrate polymers, which causes the breakdown of the middle lamella in the cell walls of cortical parenchyma [41]. Furthermore, the decrease in firmness in oranges may also be attributed to increased decay caused by *P. digitatum* fungus (Fig. 3a, b). The results illustrate the efficacy of *Z. tenuior* essential oil in inhibiting *P. digitatum* fungus (Fig. 2). Consequently, treatments involving nanocapsules, aloe gel, and essential oils, which inhibit *P. digitatum* growth in oranges, contributed to the preservation of fruit firmness (Fig. 3b, c). The enhanced antifungal properties and the coverage provided by the cuticle and lenticels in oranges coated with nanocapsules may help decrease microbial infections, respiration, and other ripening processes during storage, ultimately helping to preserve the firmness of the fruit [41].

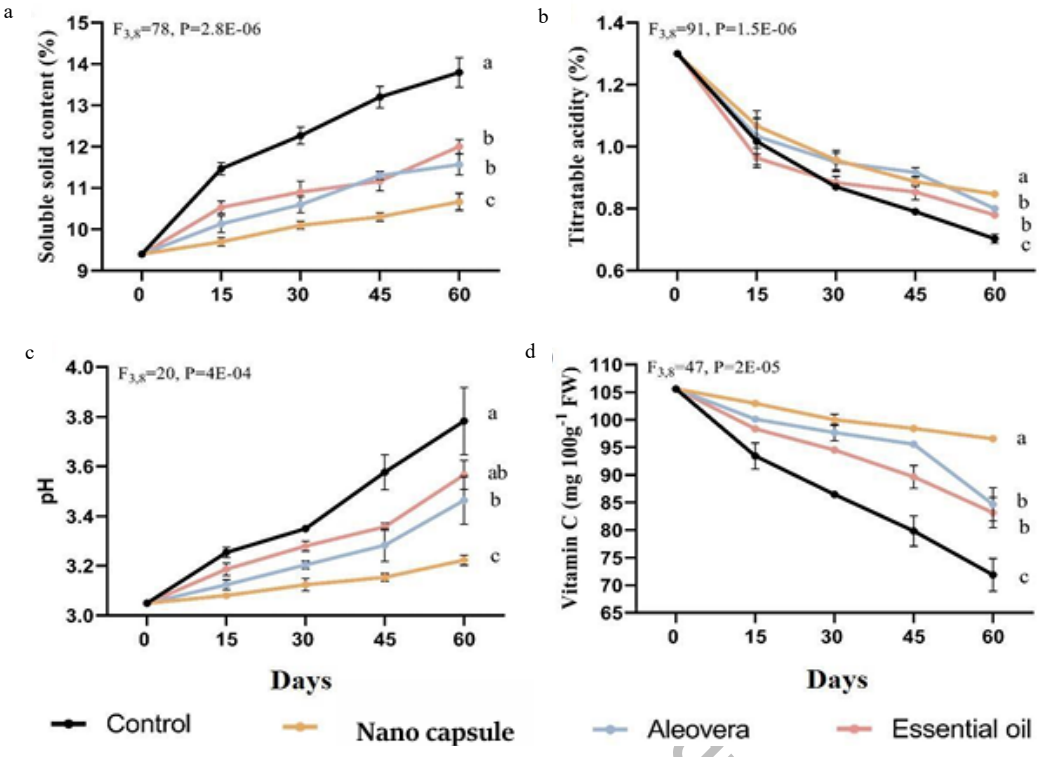


Fig. 4 Trends in soluble solid content (a), titratable acidity (b), pH (c), and Vitamin C (d) of Valencia oranges were observed. Treatments included control (no treatment), nanocapsula containing essential oil, Aloe vera gel, essential oil. Measurements were taken at 0, 15, 30, 45, and 60 days at 5 °C and 80% RH. The data represent the means of 3 oranges per treatment. Statistically significant differences are denoted by different letters (Tukey test, $p \leq 0.05$). Error bars indicate the standard deviation of the mean (SD).

There was a notable increase in soluble solid content in both the control and coated fruits during storage (Fig. 4a). This increase is attributed to fruit ripening and senescence. In control oranges, the escalation in soluble solids could stem from the breakdown or synthesis of polysaccharides into simple sugars, leading to increased moisture loss as a result of sugar buildup in the tissues [42]. This likely contributes to decreased acid content (TA) as acids play a crucial role as substrates for respiratory metabolism. However, the treatment with nanocapsule showed only aminimal increase in total soluble solid content compared to the control (Fig. 5a). Oranges coated with nanocapsules exhibited the least rise in SSC (9.4% to 10.6%) compared to control (9.4% to 13.8%) (Fig. 5A). Brandes and Zude-Sasse [43] noted that the increase in soluble solid content (SSC) in both the flesh and peel takes place when the fruits reach their climacteric respiration peak.

The titratable acidity (TA) declines in both the coated fruits and the control fruits, beginning from an initial value of 1.4 g of citric acid per liter (Fig. 4b). This decrease can be linked to the consumption of organic acids, like citric acid, during respiration. When stored at 5 °C and 80% relative humidity, the orange fruits show a comparable trend, with the titratable acidity (TA) consistently declining throughout the storage duration.

Notably, the nanocapsule treatment shows a distinct behavior, maintaining a relatively constant TA level between 30 and 60 days (0.95 to 0.84 g citric acid/L) (Fig. 4b). Thus, coating with nanocapsules helped retain the TA of oranges. We observed a direct correlation between increased SSC and decreased TA in oranges, which is consistent with other studies. The nanocapsule and Aloe-gel coatings maintained lower pH values in oranges compared to the control fruit samples (Fig. 4c). Specifically, the nanocapsule samples sustained pH values between 3.05 and 3.2 throughout the 60-day storage period, which was lower than that of the other samples (Fig. 4c). In general, the pH of fruit juice increases with the increase of storage days. As is clear from the results, as the fruit ripens, the amount of TA and ascorbic acid decreases; as a result, the pH of fruit juice increases (Fig. 4c).

Research has shown that the use of nanocapsules and Aloe vera gel can help prevent a decrease in pH during the storage period. In this study, pH values were more stable in the nanocapsule treatment compared to other treatments. Since vitamin C degradation is pH-dependent, this stability likely contributed to the preservation of vitamin C content. As storage time increased, the amount of vitamin C in the control group decreased significantly. However, coating oranges with nanocapsules effectively prevented a significant reduction of vitamin C (Fig. 4d), which could be attributed to the treatment's ability to maintain pH, soluble solids content (SSC), and titratable acidity (TA). (Fig. 4).

CONCLUSIONS

Our research demonstrated the effectiveness of natural nanocapsules, derived from Aloe vera gel and infused with *Z. tenuior* essential oil, in preserving the post-harvest quality of Valencia oranges. While all edible coatings improved fruit quality indicators, the nanocapsules containing *Z. tenuior* essential oil showed superior performance in maintaining weight, firmness, soluble solid content (SSC), titratable acidity (TA), and reducing respiration rate. Moreover, this nanoencapsulated essential oil effectively inhibited the growth of *P.digitatum*,

a major post-harvest pathogen in citrus fruits. The novelty of this study lies in the combined use of Aloe vera gel-based nanocapsules as an edible coating with encapsulated essential oils, providing a natural and sustainable alternative to synthetic fungicides and conventional preservation methods. Future research should focus on optimizing the nanocapsule formulation to enhance antifungal efficacy and coating stability, as well as conducting sensory evaluations to assess possible effects on fruit taste, aroma, and texture. Additionally, evaluating the economic feasibility and scalability of this approach for commercial application is essential. Investigating long-term effects on fruit shelf life and integrating this coating with other post-harvest treatments could also provide synergistic benefits and further improve citrus preservation.

Consent for Publication
Not Applicable.

Data Availability:
The data that support this study will be shared upon reasonable request made to the corresponding author.

Conflicts of Interest
The authors have not declared any conflict of interests.

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