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Research Paper

Investigation of functional additives in chitosan-based edible coatings and their impact on physicochemical, bioactive, and microbial stability of orange-fleshed sweet potatoes (OFSP) during storage

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ABSTRACT

The efficacy of chitosan-based edible coatings (EC) in enhancing postharvest quality and extending the shelf life of orange-fleshed sweet potatoes (OFSP) is thoroughly investigated in this study. Six EC treatments (T2-T7) containing either chitosan alone/lemongrass essential oil (LEO), and/or citric/ ascorbic acids were applied to OFSP and stored under controlled atmospheric conditions (20 °C, 75 ± 5 % RH) for 28-day period along with an uncoated sample (T1). The samples were analysed weekly for the changes in physicochemical properties (weight loss, colour and texture), total phenolic content (Folin assay), antioxidant capacity (TEAC), bioactive components (HPLC) and microbial load. The results showed that T5 (chitosan/LEOs) and T7 (chitosan/LEOs/ascorbic/citric acid) coatings were particularly effective. T5 exhibited the least weight loss (5.65 %), while T1 (uncoated samples) recorded the greatest weight loss (13.23 %) by day 28. The main phenolic compounds identified in OFSP samples were 4-Caffeoylquinic Acid (4-CQA) and 3,5-Caffeoylquinic Acid (3,5-diCQA). At the end of the storage period, T5 displayed the highest TPC of 3.33 mg GAE g^{-1}, while T7 recorded the highest β-carotene content (0.72 ± 0.09 mg g^{-1}) and were significantly different from uncoated samples ($p < 0.05$), suggesting the role of chitosan/ antioxidants in the stability of bioactive compounds. ECs especially T5 and T7 displayed strong antimicrobial properties, which were demonstrated by their significant reduction of mesophilic bacterial counts compared to the control ($p < 0.05$). This work establishes a basis for developing bioactive coatings for preserving the quality and safety of OFSP, contributing to improved food security and nutritional outcomes.

1. Introduction

Orange-fleshed sweet potatoes (OFSP) have become a vital crop in addressing vitamin A deficiency, particularly in Sub-Saharan Africa, where this deficiency is a leading cause of preventable blindness and immune system issues (Bouis et al., 2019). OFSP is rich in β-carotene, a provitamin A compound, offering a sustainable nutritional intervention against malnutrition (Islam et al., 2015; Mostafa et al., 2019). However, its broader utilisation is often limited by significant postharvest losses, which compromise both its nutritional value and marketability. These losses are largely due to the rapid degradation of key physicochemical parameters, including weight, texture, and colour, which occurs during storage. OFSP's high moisture content and susceptibility to microbial spoilage further exacerbate these challenges (Sanchez et al., 2019). β-carotene, the bioactive compound responsible for OFSP's orange hue, is highly sensitive to oxidative degradation, particularly during prolonged storage (Bengtsson et al., 2007). In addition to texture and weight, preserving the colour and β-carotene content of OFSP is essential for maintaining its nutritional and aesthetic value. As a result, there is a critical need for strategies that can extend its shelf life while maintaining its nutritional quality. Developing effective and economically viable preservation methods is essential for enhancing OFSP's role in food security and nutritional improvement, particularly in low-resource settings where cold storage infrastructure is lacking (Ali et al., 2014).

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Edible coatings (ECs) represent a promising and biodegradable strategy for mitigating postharvest losses, particularly in highly perishable crops such as orange-fleshed sweet potatoes (OFSP). By forming a protective layer around the produce, ECs effectively reduce moisture loss, regulate gas exchange, and inhibit microbial growth, thereby enhancing the shelf life and overall quality of fresh produce (Saha et al., 2014). Among various coating materials, chitosan—a biopolymer derived from chitin—has garnered significant attention due to its remarkable antimicrobial properties, excellent film-forming ability, and biocompatibility (Waimaleongora-Ek et al., 2008). Unlike synthetic alternatives, chitosan is biodegradable and non-toxic, making it a safe and environmentally friendly option for food preservation. Its antimicrobial efficacy is particularly noteworthy; it targets a broad spectrum of pathogens, including fungi and bacteria, through its polycationic nature, which disrupts microbial cell membranes and impairs cellular functions (Suseno et al., 2014; Martins et al., 2014). However, despite the documented advantages of chitosan, its specific role in preserving the nutritional and bioactive compounds of OFSP, such as β-carotene, remains inadequately investigated. This gap in knowledge highlights the necessity for further research to elucidate how chitosan-based coatings can not only extend shelf life but also maintain the health-promoting properties of OFSP, thereby maximising its potential as a functional food in combating malnutrition, particularly in regions affected by vitamin A deficiency.

In addition to chitosan, essential oils (EOs) are increasingly being incorporated into ECs to enhance their antimicrobial and antioxidant properties. Lemongrass essential oil (LEO), rich in bioactive components like citral, geraniol, and myrcene, has demonstrated potent antimicrobial activity in disrupting microbial cell membranes and inhibiting essential microbial enzymes (Azarakhsh et al., 2013; Gaspar et al., 2022). Furthermore, LEO offers significant antioxidant capacity, which is crucial for preventing the oxidative degradation of sensitive bioactive compounds like β-carotene during post-harvest storage (Burt, 2004b; Azarakhsh et al., 2013; Dharini et al., 2023). The combination of chitosan and EOs is particularly promising, as their complementary mechanisms can enhance the preservative effects of ECs. While chitosan acts as a physical barrier to moisture and oxygen, EOs provide additional antimicrobial and antioxidative protection. However, the interaction between chitosan and EOs in preserving OFSP, is not well understood, and improper formulations could lead to adverse effects, such as moisture loss (Ali et al., 2014; Dharini et al., 2023). This warrants further investigation. Apart from EOs, incorporating antioxidants like citric acid and ascorbic acid into chitosan coatings can further enhance their effectiveness in preserving postharvest quality. Citric acid, a well-known chelating agent, can inhibit enzymatic browning by reducing the activity of polyphenol oxidase (Dhall, 2013). Additionally, ascorbic acid (vitamin C) acts as a strong antioxidant, preventing oxidative stress by scavenging reactive oxygen species (ROS) and stabilising colour and texture (Bico et al., 2008). These antioxidant properties have been shown to complement the protective effects of chitosan, especially in maintaining moisture content and reducing spoilage in high-moisture crops (Robles-Sánchez et al., 2012b).

Studies have demonstrated that such ECs effectively extend shelf life, particularly in fruits and vegetables, by preventing microbial growth and slowing down respiration rates (Wang and Gao, 2012; Yadav et al., 2022). For instance, combining chitosan with ascorbic acid in the postharvest treatment of mangoes has been shown to significantly reduce weight loss and preserve colour and firmness during storage (Robles-Sánchez et al., 2012b). Similarly, citric acid, with its pH-lowering capacity, helps reduce microbial load, enhancing the overall preservation effect of the coating (Cazón et al., 2016). Based on the reported protective effects of these chitosan-based coatings in other food crops, this study aimed to evaluate the effects of chitosan-based ECs, with or without functional additives (FAs) such as lemongrass EO and antioxidants (citric acid & ascorbic) on the physicochemical attributes, bioactive components and microbiological stability of OFSP during postharvest storage. Specifically, this research focuses on key quality parameters, including weight loss, texture, colour retention; bioactive properties such as individual phenolic compounds, β-carotene stability, and the microbial load over a 28-day period under controlled environmental conditions. The findings will contribute to postharvest management strategies that address food security and dietary challenges, particularly in regions where OFSP serves as a staple crop and postharvest losses hinder its full potential.

2. Materials & methods

2.1. Chemicals

Chitosan (98 % deacetylated, molecular weight: 250–300 kDa) was sourced from ChitoLytic Inc. (Toronto, Canada). Acetic acid, glycerol, ascorbic acid, citric acid, Polysorbate-80, calcium chloride, sodium hypochlorite, caffeic acid, neochlorogenic acid, 4-O-Caffeoylquinic acid, 3, 4-Caffeoylquinic Acid, 3, 5-Caffeoylquinic Acid, 4, 5-Caffeoylquinic Acid (3,4-diCQA, 3,5-diCQA, 4,5-diCQA), methanol (≥99.9 %, HPLC grade), ethanol, and Folin-Ciocalteu's Phenol reagent were obtained from Sigma-Aldrich Co. Ltd. (St. Louis, MO, USA). Sodium carbonate and chlorogenic acid were acquired from Fluorochem Ltd. (Hadfield, UK). Trifluoroacetic acid (HPLC grade) was supplied by Alfa Aesar. 2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) was purchased from Biotium (Fremont, CA, USA), while Phosphate Buffered Saline (PBS, 10x) was obtained from G-Biosciences (St. Louis, MO, USA). Ethanol was sourced from VWR International Ltd. (Lutterworth, UK) and microbial media components, including PCA, MRS, MAC, PDA, and PB, were supplied by Thermo Fisher Scientific Inc. (Waltham, Massachusetts, USA).

2.2. Plant materials

Orange-fleshed sweet potato tubers (OFSP) were obtained from Tesco Express PLC (UK). Thirteen packets (13 × 1 kg) were selected for uniformity in freshness, size, shape, and colour, resulting in 104 disease-free tubers designated for the study. These tubers were divided into seven groups, each consisting of 14–15 tubers, for various treatments and were washed, disinfected, and processed immediately. Additionally, lemongrass essential oil (LEO) was sourced from Agro Park Limited Company (Ikoyi, Lagos, Nigeria).

2.3. Sample preparation and pre-treatment

Whole, uncut OFSP samples underwent a thorough pre-washing under running tap water for 5 min to remove surface dirt and contaminants. Following this, the samples were immersed in a 2 % sodium hypochlorite solution for 5 min to achieve surface sterilisation, effectively reducing microbial contaminants. The samples were then rinsed with distilled water to eliminate any residual disinfectant. These washing and disinfection steps were critical to ensure the OFSP tubers were free from agrochemical residues and maintained their initial microbiological quality prior to coating treatments.

2.4. Preparation of edible coating (ECs) solutions and tuber treatment protocol

Seven treatments, including an uncoated control, were formulated to evaluate the efficacy of various chitosan-based ECs combined with functional additives, which have been detailed in Table 1.

2.5. Post-treatment incubation and monitoring

After applying chitosan-based ECs, OFSP tubers were incubated at 25 °C (75 ± 5 % RH) in homeostatic incubators (WhitePython® Reptile Egg Incubator) to simulate real-world environmental conditions. Seven

Table 1
Composition and Preparation Protocols of Chitosan-Based Edible Coatings and Control Treatment for OFSP Quality Evaluation.

Treatment	Composition	Preparation Protocol	Duration of Treatment
T1	Uncoated Control	No coating; serves as a baseline for comparison.	None.
T2	1 % Chitosan (w/v)	Chitosan solutions were prepared by dissolving 1 % (w/v) chitosan powder in distilled water, which was acidified with 10 mL L^{-1} acetic acid. The mixture was continuously stirred and heated to 50 °C to facilitate dissolution, with intermittent sonication for 20 mins to achieve a homogenous solution.	Samples were treated for 1 min and then dried for 24 hrs.
T3	1 % Chitosan (w/v)	Chitosan solution was prepared as described in T2.	Samples were treated for 5 min and then dried for 24 hrs.
T4	0.1 % Lemongrass EO (v/v)	The solution was prepared by dissolving 1 mL of lemongrass EO per litre of distilled water, stabilised with 4 mL of food-grade Polysorbate 80 (an emulsifier), and homogenised at 12,800 rpm for 5 min using a high-speed homogeniser.	Samples were treated for 1 min and then dried for 24 hrs.
T5	1 % Chitosan (w/v) + 0.1 % Lemongrass EO (v/v)	Chitosan solution was prepared as described in Treatment 2, after which lemongrass EO was added at a 0.1 % concentration, along with 4 mL of food-grade Polysorbate 80. The mixture was then homogenised at 12,800 rpm for 5 mins.	Samples were treated for 1 min and then dried for 24 hrs.
T6	1 % Chitosan (w/v) + 1.5 % Glycerol (v/v) + 2 % Calcium Chloride (w/v) + 1 % Ascorbate (w/v) + 1 % Citrate (w/v)	Distilled water was acidified with citric acid (10 g L^{-1}) and ascorbic acid (10 g L^{-1}) while being continuously stirred and gently heated to 40 °C. Chitosan powder (20 g L^{-1}) was added to the acidified water under continuous stirring to ensure even dispersion, with intermittent sonication applied as necessary to aid in complete dissolution. In a separate container, glycerol (15 mL L^{-1}) and calcium chloride dihydrate (20 g L^{-1}) were dissolved in distilled water. All solutions were then combined under constant stirring to ensure thorough mixing. The resulting mixture was homogenised at 12,800 rpm for 10 mins to produce a uniform coating solution, with the final volume adjusted using distilled water as needed.	Samples were treated for 5 min and then dried for 24 hrs.
T7	1 % Chitosan (w/v) + 1.5 % Glycerol (v/v) + 2 % Calcium Chloride (w/v) + 1 % Ascorbate (w/v) + 1 % Citrate (w/v) + 0.1 % Lemongrass EO (v/v)	Chitosan solution was prepared as described in Treatment 6. Additionally, lemongrass EO (1 mL L^{-1}) was dissolved in distilled water containing 4 mL of food-grade Polysorbate 80, using a homogeniser at 12,800 rpm for 5 mins to ensure proper stabilisation.	Samples were treated for 5 min and then dried for 24 hrs.

incubators accommodated the seven treatment groups, preventing cross-contamination. Sodium chloride (20 g NaCl: 10 ml water) was placed inside the chambers to regulate moisture and maintain humidity. The incubators operated continuously for 28 days, with tuber samples retrieved only for weekly analysis. To minimise disruptions, the incubators were opened exclusively at specified intervals, to collect samples. After drying and incubation, the OFSP samples were peeled, processed, and freeze-dried (Alpha 1–4 LD, Martin Christ Gefriertrocknungsanlagen GmbH, Germany), following which the samples were ground into a fine powder and stored at –20 °C until further analysis. Weekly assessments of quality parameters, along with biochemical and microbiological evaluations, were conducted during the 28-day period, with measurements taken on days 0, 7, 14, 21, and 28 to monitor changes and evaluate treatment effects.

2.6. Quality parameter evaluation

2.6.1. Determination of tuber weight loss

Weight loss of OFSP tuber samples was monitored weekly using an analytical balance (Fisherbrand RS232, Fisher Scientific Ltd., Cambridge, UK). The initial weight of each sample was recorded prior to incubation and post-treatment application. Weights were subsequently measured weekly before further analyses to track changes during storage. Systematic measurements ensured accurate monitoring of weight variations in response to the different treatments. Weight loss was expressed as a percentage of the initial weight, calculated using the following equation: where w_1 represents the initial weight (g), and w_2 represents the weight (g) recorded during each weekly analysis.

$$\textit{Weight Loss}\ (\%) = ((w_1 - w_2)\,/\,w_1) \times 100$$

This calculation facilitated a comparative assessment of weight loss between coated and uncoated tubers throughout the 28-day storage period.

2.6.2. Determination of colour

Colour parameters of coated and uncoated OFSP tuber samples were assessed weekly by extracting a 2 cm thick disc from the median section of each tuber for analysis. Colour measurements were recorded using a PCE-CSM 1 colourimeter (PCE Instruments Ltd., Manchester, UK). The instrument measured the following colour parameters: L* (lightness): 0 (dark) to 100 (bright), a* (+a*: redness, −a*: greenness), b* (+b*: yellowness, −b*: blueness). To further assess colour characteristics, the hue angle (h°) and chroma (C*) were calculated using the equations described by Pathare et al. (2012):

$$C* = \sqrt{a^2 + b^2}$$

$$H^0 = Tan^{-1}(b / a)$$

Calibration of the colourimeter was performed with both black and white plates to ensure measurement accuracy. Each experiment was conducted in duplicate to ensure reliable and consistent results throughout the 28-day storage period.

2.6.3. Determination of firmness

The firmness of both coated and uncoated OFSP tuber samples was assessed using a TA.XT+ texture analyser (Stable Micro Systems Ltd., Godalming, UK) equipped with a Standard Blade Set (HDP/BS) and Warner Bratzler Blade. A 2 cm thick disc was cut from the median section of each tuber for analysis. Firmness was measured by assessing the force (g) exerted on the tuber slices as they were cut by the probe, which operated at a speed of 5.0 mm s^{-1} with a displacement of 25 mm. This method provided insights into the effects of various coating treatments on the textural characteristics of the OFSP tubers. All measurements were conducted in triplicates to ensure the reliability and accuracy of the results.

2.7. Metabolite and biochemical assessment

2.7.1. Extraction of bioactive components from orange-fleshed sweet potatoes (OFSP)

For the extraction of phenolic compounds and bioactive components, 1 g of the powdered OFSP from each group was mixed with 5 mL of 80 % methanol for polyphenol extraction. The mixture was vortexed (Wizard Advanced IR, VELP Scientifica Srl, Italy) for 1 min and subjected to ultrasonic treatment in a water bath (LSB 12 Aqua Pro XUB18, Grant Instruments Ltd, UK) at 40 °C for 30 min. Following ultrasonication, the homogenates were centrifuged at 4000 rpm for 10 min (Allegra X-22, Beckman Coulter Ltd, UK). The supernatants were carefully collected for subsequent biochemical analyses, including total phenolic content (TPC) and antioxidant capacity (TEAC) assays.

For β-carotene extraction, 1 g of powdered sample was weighed into tubes and 10 ml of a solution comprising of 80 % petroleum ether and 20 % acetone was added to the powdered sample. These were then mixed using a vortex machine until completely dissolved, the tubes were then kept in a shaker-water bath for 20 min at 20 °C for extraction of β-carotene. Subsequently, the mixture was centrifuged at 4000 rpm for 5 min, and the supernatant was collected in fresh tubes. This supernatant was then concentrated (Techne Dri-Block) and re-dissolved in 5 ml of tetrahydrofuran prior to HPLC analyses. All samples were subjected to identical processing conditions to maintain uniformity in the biochemical analyses. All extractions and analysis were performed in triplicate (n = 9) to ensure accuracy and reliability.

2.7.2. Determination of antioxidant capacity (TEAC)

The antioxidant capacity of OFSP samples was determined using the Trolox Equivalent Antioxidant Capacity (TEAC) assay modified from Graham (1992). A polyphenol extract (1 mL) from each sample was diluted 15-fold with 80 % methanol. Subsequently, 40 μL of the diluted extract or Trolox (antioxidant standard) was mixed with 2 mL of ABTS (2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) reagent. The mixture was incubated at room temperature for 5 mins, after which absorbance was measured at 734 nm using a spectrophotometer. The ABTS reagent was prepared and incubated in the dark for 24 hrs for colour development and adjusted with PBS buffer to achieve a stable absorbance of 0.7 ± 0.02 at 734 nm. Trolox was used as the antioxidant standard, and a calibration curve was generated using concentrations of 0, 20, 40, 60, 80, and 100 μg mL^{-1}. Antioxidant capacity for each sample was calculated based on this standard curve and expressed as millimoles of Trolox equivalents per gram of dry sample (mM TE g^{-1} dry sample) freeze-dried weight (FDW).

2.7.3. Determination of total polyphenol content (TPC) by Folin-Ciocalteu method

Total polyphenol content (TPC) was measured using a modified method based on Ifie et al. (2016). Briefly, 1 mL of OFSP extract was diluted with 9 mL of 80 % methanol. The assay commenced by mixing 1 mL of the diluted extract with 5 mL of 10 % Folin-Ciocalteu reagent, followed by the addition of 4 mL of 7.5 % sodium carbonate. The mixture was incubated in a water bath at 50 °C for 30 min and the absorbance measured at 760 nm. TPC was calculated using a gallic acid standard curve and the results were expressed as milligrams of gallic acid equivalent per gram of dry sample (mg GAE g^{-1} dry sample) freeze-dried weight (FDW).

2.7.4. HPLC analysis of phenolic compounds and β-carotene

Quantification of phenolic acid compounds and β-carotene was performed using a Shimadzu HPLC system (Shimadzu Scientific Instruments Inc., Kyoto, Japan) according to our previously established protocol (Ifie et al., 2017). The mobile phase consisted of solvent A (0.1 % trifluoroacetic acid (TFA) in Milli-Q water) and solvent B (50 % acetonitrile with 0.1 % TFA). The analysis was conducted over 40 min at a flow rate of 1 mL min^{-1}, with an injection volume of 10 μL using a Phenomenex Gemini C18 column (5 μm, 250 mm × 4.6 mm) with the temperature set at 35 °C. Standard solutions were prepared for phenolic acids, including caffeic acid, chlorogenic acid, neochlorogenic acid, 4-O-CQA, 3,4-diCQA, 3,5-diCQA and 4,5-diCQA. Analytes were detected at 320 nm using a photodiode array detector. Concentrations of individual phenolic acids were determined from calibration curves, and data analysis was performed using Shimadzu LabSolutions software.

For β-carotene analysis, the mobile phase comprised solvent A (methanol, 95:5, with 10 mM ammonium acetate) and solvent B (methyl tert-butyl ether). A gradient elution was employed, starting with 85 % solvent A and gradually transitioning to 63 % solvent B over 35 min. The flow rate was set at 0.9 mL min^{-1}, with β-carotene detected at 450 nm. Concentrations of β-carotene were quantified using standard curves and expressed as milligrams of β-carotene per gram of sample (mg β-carotene g^{-1} dry sample) freeze-dried weight (FDW).

2.8. Microbiological safety and quality assessment

2.8.1. Sample preparation and serial dilution

For microbiological analyses, 1 g samples were aseptically taken from the interior of OFSP tubers using a sterile scalpel to minimise external contamination. Samples were rinsed with sterile water to remove superficial microorganisms, ensuring microbial counts reflected intrinsic contamination. Each 1 g sample was homogenised in 9 mL of 0.1 % peptone water, creating a suspension that maintained microbial viability without promoting growth. Serial dilutions were performed by transferring 1 mL of the homogenised sample into 9 mL of sterile 0.1 % peptone water, repeating the process until a final dilution of 1:10,000,000 was achieved. This ensured that microbial counts on agar plates would fall within a countable range (30–300 CFU mg^{-1}), preventing overgrowth or sparsity of colonies that could impede accurate enumeration.

2.8.2. Plating on selective media and incubation conditions

Selective media were used to isolate specific microbial groups by inoculating 200 μL of diluted samples onto different media types. Plate Count Nutrient Agar (PCNA) was utilised for total bacterial counts, MRS Agar (MRSA) was used to quantify lactic acid bacteria (LAB), with plates incubated at 37 °C for 48 h. MacConkey Agar (MAC) was employed for enumerating coliform bacteria, incubated at 37 °C for 24 hrs. Finally, Potato Dextrose Agar (PDA) was employed to detect moulds, yeasts, and fungi, with incubation at 28 °C for 48 to 96 hrs.

2.8.3. Colony counting and enumeration

Bacterial colonies were counted using a light magnifier on plates

containing 30 to 300 colonies to minimise errors from overcrowding. For yeasts and moulds, distinguishable colonies were manually counted. Colony counts were expressed as colony-forming units (CFU) per gram of the original sample and reported as logarithmic values ($\log_{10}$ CFU g^{-1}) to accommodate variations in microbial populations.

2.9. Statistical analysis

Statistical analysis was performed using IBM SPSS software (v29.0; SPSS Inc., Chicago, Illinois, USA). Data were evaluated using two-way analysis of variance (ANOVA) to assess the impact of various treatments. Post-hoc comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test or Duncan's Multiple Range Test, depending on the analysis, to identify significant differences between treatment means. Statistical significance was determined at a threshold of $p \leq 0.05$, ensuring robust analysis across experiments.

3. Results and discussion

3.1. Physical quality parameter analysis

3.1.1. Evaluation of tuber weight loss

The study's findings demonstrate that the various treatments applied to the tubers had distinct impacts on their wet weight over the 28-day observation period as reflected in Fig. 1. The percentage of weight loss exhibited a consistent increase throughout this period. Control samples (T1) experienced the highest weight reduction, culminating in a 13.23 % loss by day 28. This significant weight loss in the uncoated T1 samples underscores the critical role of a protective barrier in mitigating moisture loss, a primary driver of weight reduction. The observed weight loss in OFSP tubers is primarily attributable to post-harvest physiological activities such as transpiration and enzymatic reactions, particularly through the respiration processes of the tubers (Zhuang et al., 2011; Wang and Gao, 2012). Moreover, the rate of water evaporation is largely influenced by the water vapour pressure gradient between the tuber skin and the surrounding atmosphere, which is further affected by storage conditions (Yousuf et al., 2021). The efficacy of coatings in reducing weight loss is crucial, as moisture loss not only diminishes the nutritional quality of produce but can also lead to undesirable changes in texture and flavour, ultimately affecting consumer acceptance (Truong et al., 2018). The reduction in weight loss also correlates with the retention of bioactive compounds, including vitamins and antioxidants, which are vital for maintaining the health benefits associated with OFSP (Van Chuyen et al., 2013).

Among the EC treatments, T5 demonstrated the most effective performance in minimising weight loss, with only a 5.65 % reduction by day 28. This outcome suggests that the combination of chitosan and LEO concentration, employed in T5 forms a highly effective barrier against moisture loss. Such efficacy aligns with the results of Minh (2018), who reported that chitosan, when combined with low concentrations of essential oils, effectively reduced weight loss and slowed the rate of moisture evaporation in cantaloupe (*Cucumis melo* L.). Research has shown that the interaction between chitosan and essential oils can be complex. In a related study, Gago et al. (2020) investigated the effects of nanocoating enriched with essential oils on the long-term storage of 'Rocha' pears. They highlighted that high concentrations of LEO can compromise the moisture barrier, potentially leading to increased water loss during storage. The data (Fig. 1, day 28) also showed that T4 incorporating only water and LEO, achieved the highest weight loss of 12.70 % after the control samples. Thus, the lack of protective film-forming substances in this coating treatment may have contributed to this outcome, suggesting that the balance between moisture retention and moisture loss is critical (Jiang et al., 2023). It is noteworthy that weight loss in coated samples apart from T4 was less than 5 % for the

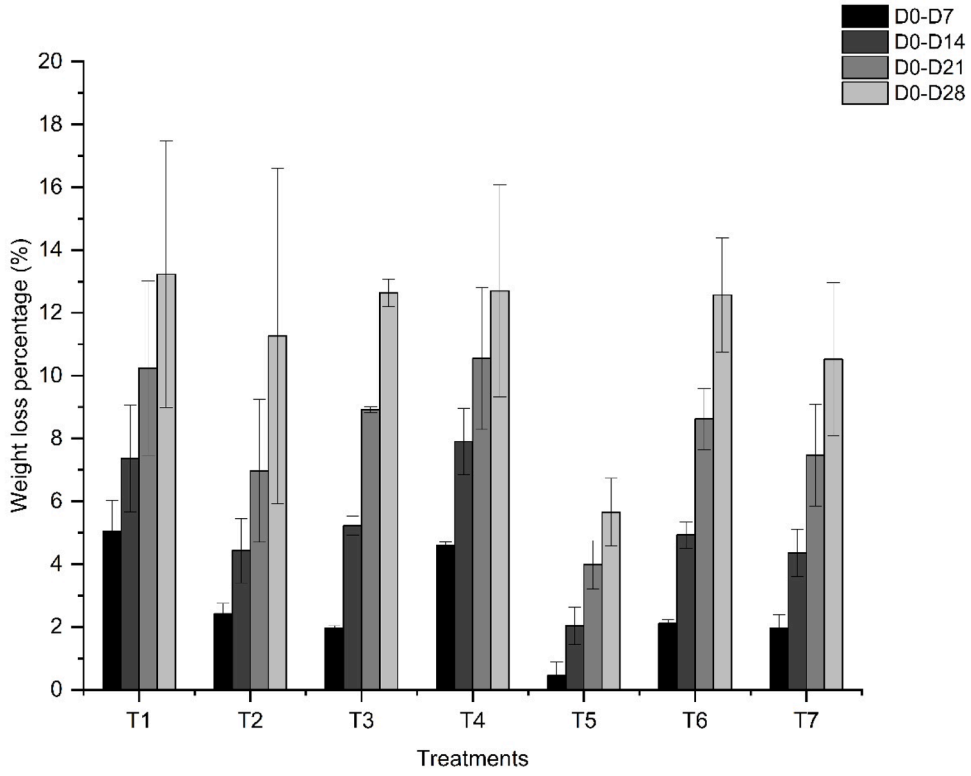

Fig. 1. Weight Loss Percentage (%) of Orange-Fleshed Sweet Potatoes (OFSP) During a 28-Day Storage Period Across Various Treatments.
This figure illustrates the percentage of weight loss in OFSP tuber samples subjected to seven different treatments, including an uncoated control. The x-axis represents the various treatments, while each bar corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the weight loss percentage. Each treatment is represented by distinct bars for different analysis days, demonstrating the effectiveness of various coatings in minimising moisture loss.

first 14 days, but rapidly increased after that, suggesting that while the coatings applied in these treatments were initially effective in retaining moisture, their effectiveness diminished over time. The increase in weight loss observed after day 14 necessitates further investigation into the integrity and long-term effectiveness of the coating formulation.

3.1.2. Colour measurement and deviation

Colour stability is crucial for the consumer acceptance and marketability of OFSP tubers. The current study employed CIELAB colour scales, which are widely recognised in the food industry for evaluating product quality (Nurfarhana et al., 2019). Over a 28-day storage period, the study meticulously assessed colour stability through key parameters: lightness (L*), redness (a*), and yellowness (b*), focusing on the influence of various chitosan-based ECs. Table 2 illustrates that all treatments exhibited a significant decline in L* values, with treatment T1 starting at 79.11 ± 1.40 on day 0 and decreasing to 76.57 ± 0.77 by day 28. This reduction indicates that pigment degradation and moisture loss are pivotal factors affecting the quality of OFSP (Yuan et al., 2015; Rosero et al., 2022). The consistent decline across treatments supports the hypothesis of ongoing enzymatic browning and respiration, which are common phenomena in post-harvest processes (Wang and Gao, 2012; Ali et al., 2014; Nurfarhana et al., 2019). Furthermore, certain EC treatments demonstrated protective effects on carotenoids, emphasising their potential to mitigate colour loss and enhance the shelf life of OFSP (He et al., 2016; Stoll et al., 2017; Nurfarhana et al., 2019). The nuanced interactions between the treatments and pigment stability underscore the necessity for tailored EC solutions to address specific post-harvest challenges (Oyom et al., 2021).

The decrease in chroma (C*) values across all treatments indicates that colour intensity is directly related to pigment concentration, particularly as moisture levels diminish during storage (Rodríguez-Amaya, 2018). Notably, treatment T1 exhibited a decline from 62.00 ± 1.40 on day 0 to 52.99 ± 0.77 by day 28, reflecting a statistically significant drop ($p < 0.05$). This decline is corroborated by weight loss analyses, which indicate that moisture loss accelerates the oxidative degradation of pigments (Wang and Gao, 2012). The ability of chitosan to serve as an effective oxygen barrier is critical in preserving the natural colour of OFSP by preventing oxidative damage to carotenoids (Dong et al., 2003). Although the overall trends suggest effective colour preservation, the hue angle (h°) revealed a gradual increase across treatments, with treatment T4 showing a significant rise from 0.94 ± 1.12 to 1.03 ± 3.43. This increase suggests a shift in colour positioning but does not correlate directly with reduced vibrancy, which is primarily linked to chroma levels. The findings imply that while chitosan ECs can delay pigment degradation, they do not completely halt it, a challenge commonly encountered in the storage of carotenoid-rich produce (Rodríguez-Amaya, 2018).

To further enhance the colour stability of OFSP, the integration of chitosan with essential oils (LEO) has emerged as a promising strategy. Essential oils are known for their antioxidant properties, which can

Table 2
Colourimetric Values (L*, a*, b*, C*, hº) of Orange-Fleshed Sweet Potatoes (OFSP) Across Different Chitosan-based EC Treatments.

Treatment	Day 0	Day 7	Day 14	Day 21	Day 28
L*					
T1	79.11±1.40	71.84±0.93$^{\#}$	72.06±1.13$^{\#}$	74.54±1.53	76.57±0.77
T2	77.68±4.80	71.78±1.73	73.27±1.11	73.03±0.58	75.10±0.01
T3	79.41±0.26	69.82±0.93$^{\#\#}$	73.09±1.65$^{\#}$	74.47±0.16$^{\#}$	74.97±0.83$^{\#\#}$
T4	79.27±0.33	72.68±1.49$^{\#\#}$	72.08±1.90$^{\#}$	73.97±1.93	76.19±0.37$^{\#\#}$
T5	79.11±1.40	70.81±0.47$^{\#}$	70.51±1.00	77.28±1.15*	73.58±4.15*$^{\#}$
T6	77.68±4.80	73.11±0.68$^{\#\#}$	73.05±0.93$^{\#\#}$	75.67±0.51$^{\#}$	74.31±2.26$^{\#}$
T7	79.39±0.26	72.11±1.83$^{\#}$	71.14±0.46$^{\#}$	74.99±0.71	74.92±1.01$^{\#}$
a*					
T1	39.89±4.98	30.01±0.52	30.42±0.31	30.33±0.00	28.40±1.18
T2	35.95±2.02	30.45±0.93	30.30±0.14	31.39±0.38*	30.81±0.84$^{\#}$
T3	37.96±1.32	30.79±0.04$^{\#}$	29.31±1.70$^{\#}$	30.74±0.62$^{\#***}$	29.55±0.37$^{\#\#}$
T4	35.25±4.60	30.23±0.91	30.32±0.91	31.52±0.89	29.57±0.71
T5	40.60±7.86	30.85±0.14*	31.37±1.27*	29.92±0.06**	29.63±0.62
T6	39.68±3.69	29.87±1.16	29.48±0.50	29.89±1.52	30.03±0.06$^{\#}$
T7	38.06±2.44	30.65±0.54$^{\#}$	30.92±0.07*	29.76±0.04**	30.38±1.00$^{\#*}$
b*					
T1	47.47±2.84	48.32±2.59	48.03±3.76	48.23±2.27	44.74±4.02
T2	50.40±8.13*	49.41±3.10	48.88±1.58	49.74±4.71	49.39±3.97
T3	48.64±0.22	52.27±0.04$^{\#\#}$	47.89±2.57	48.99±0.07	45.95±2.17$^{\#\#}$
T4	48.01±1.12	50.86±3.43$^{\#}$	50.53±2.57	49.37±2.96	43.30±4.38$^{\#\#}$
T5	43.28±7.62	51.30±0.25*	52.12±4.12	44.49±0.73	45.20±0.81
T6	48.46 ± 1.26	47.88±3.90	46.91±0.86	47.83±3.61	48.13±0.21
T7	45.36±5.33	49.87±2.59	53.11±1.85*	46.76±1.15	48.76±4.92
Chroma (C*)					
T1	62.00±1.40	56.88±0.93$^{\#}$	56.85±1.13	56.97±1.53	52.99±0.77$^{\#\#}$
T2	62.49±4.80*	58.04±1.73*	57.51±1.11	58.82±0.58	58.21±0.01*
T3	61.70±0.26	60.66±0.93*	56.14±0.95$^{\#\#}$	57.83±0.16$^{\#\#}$	54.63±0.83$^{\#\#\#}$
T4	59.60±0.33	59.16±1.49$^{\#}$	58.92±1.90	58.57±1.93	52.43±0.37$^{\#\#\#}$
T5	59.34±2.93*	59.86±0.47*	60.83±1.00*	53.61±1.15*	54.13±4.15
T6	62.63±0.18	56.43±0.68$^{\#\#\#}$	55.40±0.93$^{\#\#}$	56.39±0.51$^{\#\#}$	56.75±2.26$^{\#\#\#}$
T7	59.21±1.88	58.53±1.83	61.45±0.46**	55.42±0.71	57.45±1.01**
Hue Angle (hº)					
T1	0.87±2.84	1.02±2.59	1.01±3.76	1.01±2.27	1.01±4.02
T2	0.94±8.13*	1.02±3.10	1.02±1.58	1.01±4.71	1.01±3.97
T3	0.91±0.22	1.04±0.02	1.02±2.57	1.01±0.07	1.00±2.17
T4	0.94±1.12	1.03±3.43$^{\#}$	1.03±2.57	1.00±2.96	0.97±4.38
T5	0.82±7.62	1.03±0.25	1.03±4.12	0.98±0.73	0.99±0.81
T6	0.88±1.26	1.01±3.90$^{\#}$	1.01±0.86	1.01±3.61	1.01±0.21
T7	0.87±5.33	1.02±2.59	1.04±1.85	1.00±1.15	1.01±4.92

Values are Mean ± SD. Chroma Values are in CIELAB units and Hue Angles are in radians. Values in the same treatment group (with respect to control, T1) denoted by *, and values across different observation days (with respect to day 0) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by $^{\#,\#\#,\#\#\#,}$ indicate a significant difference ($p < 0.05$, $p< 0.005$ and $p<0.0005$ respectively) based on the Tukey HSD comparison test.

augment the effects of chitosan ECs by scavenging free radicals and stabilising pigments (De Souza Gomes et al., 2016; Bhandari et al., 2022). The incorporation of these natural additives not only improves the aesthetic appeal of OFSP tubers but also enhances their nutritional value by preserving bioactive compounds associated with colour, such as carotenoids (Rojas-Graü et al., 2009; Das et al., 2021; Pandey et al., 2022). The combined application of chitosan and LEO, as evidenced by the significant maintenance of chroma and L* values across treatment groups (e.g., T3′s C* remained at 54.63 ± 0.83 on day 28), suggests a synergistic interaction that could effectively prolong the shelf life of OFSP. These findings emphasise the importance of ongoing research into innovative preservation techniques that leverage the properties of natural biopolymers and functional additives to safeguard the quality of OFSP. Ultimately, these EC formulations will enhance both the storage life and marketability of OFSP, thereby contributing to increased consumer satisfaction and nutritional intake, vital for addressing food security issues associated with staple crops.

3.1.3. Texture and firmness assessment

The firmness of fruits and vegetables is intrinsically linked to the composition and structure of their cell walls. The observed loss of structural integrity (Fig. 2) in the tubers can be attributed to the degradation of the cell wall and middle lamella, primarily due to the hydrolysis of starch and the breakdown of sugars and pectin (Ertan et al., 2023). This degradation process is exacerbated by environmental factors such as temperature and humidity, which influence the enzymatic activities that lead to texture loss (Ruttarattanamongkol et al., 2015; Malik et al., 2017). The study revealed significant variations in textural properties across the different treatments, with a general decline in firmness over time. This reduction in firmness resulted in observable delays and increased noise in the texture graphs, leading to fewer clean breaks in the slices.

The control sample (T1), exhibited a decline in firmness from 21,816.55 ± 945.84 g on day 0 to 20,971.50 ± 34.24 g on day 28, representing a 4.03 % loss of firmness. This suggests that the absence of a protective coating led to moisture loss and enzymatic degradation, compromising the structural integrity of the tubers. The inherent tendency of OFSP to lose firmness over time when stored without protective measures is likely due to ongoing moisture loss and enzymatic activity, corroborating findings from Mudyantini et al. (2023). The loss of texture in fruits and vegetables is a key indicator of the onset of ripening and senescence processes, primarily driven by an imbalance in the oxidative/antioxidant system in the absence of protective measures, as noted by Nzimande et al. (2024). These changes highlight the importance of effective coatings in maintaining textural integrity, as deterioration in texture can influence consumer acceptance and marketability (Nair et al., 2020).

T2 initially showed an improvement in structural integrity, with a peak firmness of 21,245.90 ± 33.34 g on day 7. However, this value subsequently declined, resulting in a 5.02 % reduction by day 28. Chitosan, known for forming a protective layer, has shown positive results in extending the shelf life of roots and tubers; however, its efficacy depends on factors such as viscosity and coating dispersion, which are influenced by immersion time (Tamer and Çopur, 2010b). T4 displayed a fluctuating decline in texture, from 19,879.00 ± 60.11 g on day 0 to 20,378.45 ± 99.75 g on day 14 to 20,361.80 ± 69.52 g on day 28, although less severe compared to T3 (23,614.50 ± 460.45 g; 18,248.90 ± 524.18 g; 15,098.60 ± 0.88 g respectively), indicating the need for careful formulation when incorporating EOs into coatings, as excessive concentrations may disrupt the overall functionality of the coating (Minh, 2018).

T6 and T7 demonstrated moderate effectiveness, with initial

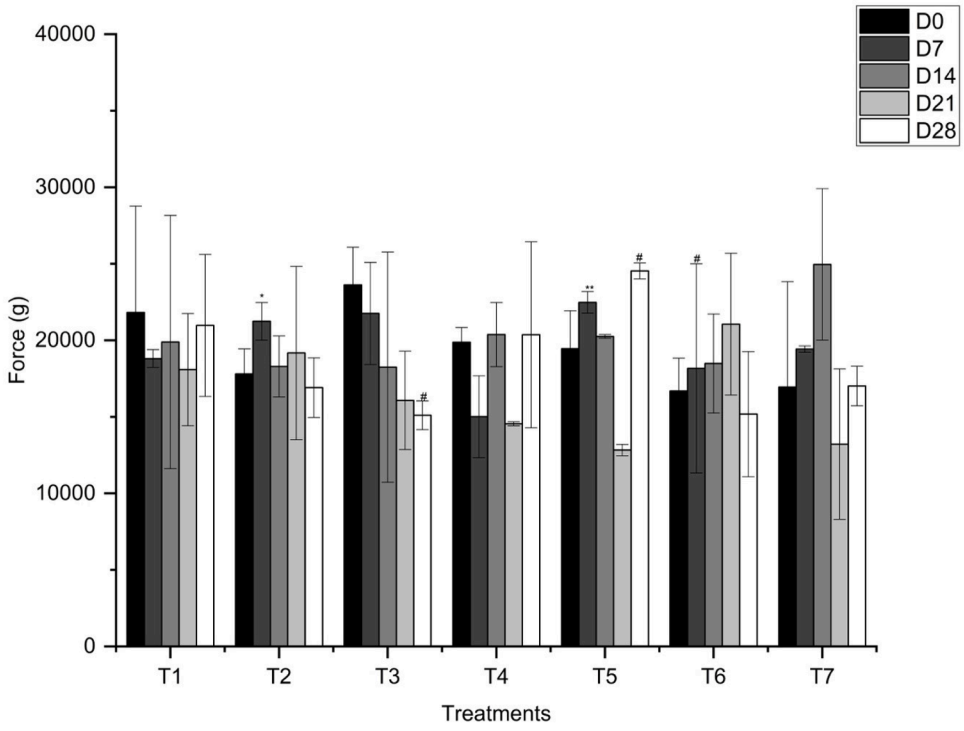

Fig. 2. Firmness of Orange-Fleshed Sweet Potatoes (OFSP) Throughout a 28-Day Storage Period Across Various Treatments.
This figure presents the firmness measurements (in grams) of OFSP tuber samples subjected to seven different treatments, including an uncoated control. The x-axis represents the various treatments, while each bar corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the force required to penetrate the tuber samples. Each treatment is represented by distinct bars for different analysis days, illustrating the variations in texture preservation. Error bars represent standard deviations, and statistically significant differences are indicated where applicable. Values in the same treatment group (with respect to control, T1) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by #, ##, ###, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

increases in firmness of 47.24 % on day 14 (18,481.90 ± 236.29 g; 24,959.00 ± 949.75 g) and 26.21 % on day 21 (21,056.10 ± 30.42 g; 13,214.80 ± 14.11 g), respectively, followed by a decline by day 28 (15,175.35 ± 88.14 g; 17,016.35 ± 1.15 g). Interestingly, the T5 samples exhibited an initial loss in firmness followed by a significant increase ($p < 0.05$), reaching 24,534.60 ± 3.12 g on day 28, representing a 26.20 % improvement. This suggests that the combination of chitosan and LEO (T5) not only preserved texture but also enhanced it. The interaction between the coating components and the tuber skin likely reduced oxygen concentration and increased carbon dioxide levels, thereby decreasing enzyme activity and helping to maintain firmness during storage (Rojas-Graü et al., 2009). These findings can be corroborated by studies of Minh (2018), which indicated that chitosan effectively prevents moisture loss, aiding in the retention of weight and texture. Overall, the effect of ECs on the texture of OFSP was less pronounced and modulated more by the intrinsic factors of the individual OFSP tubers.

3.2. Quantification of bioactive compounds and antioxidant properties

3.2.1. Total phenolic content (TPC) quantification

Total phenolic content (TPC) is a crucial parameter for evaluating the postharvest quality of fresh produce, comprising a broad range of phytochemicals that provide significant health benefits, including reduced risks of myocardial infarction, arteriosclerosis, diabetes, stroke, and cognitive impairment (Fraga et al., 2019). The protective role of polyphenols extends beyond health benefits, as they also help maintain postharvest quality and extend shelf life by acting as anti-stress and anti-senescence agents (Ishkeh et al., 2021). Research has shown that TPC is closely associated with the overall quality and marketability of fruits and vegetables, underscoring the importance of effective preservation techniques to retain these valuable compounds (Zheng and Wang, 2001).

The analysis of total phenolic content (TPC) across treatments revealed significant differences throughout the storage period (Fig. 3). At day 0, TPC values ranged between 0.98 ± 0.17 and 2.48 ± 0.82 mg GAE g^{-1} FDW across treatments, showing no significant difference. By day 7, an increase in TPC was observed across most treatments, with T2 and T6 reaching 1.34 ± 0.03 and 1.34 ± 0.27 mg GAE g^{-1} FDW, respectively. The increase in TPC is attributed to the antioxidant properties and the gas-barrier properties of the chitosan ECs,as well as that of ascorbic acid, and LEO, which formed a protective barrier, suppressing polyphenol oxidase (PPO) activity and limiting oxidative degradation of phenolics (Zam, 2019; Viacava et al., 2022). Treatments T2 and T6 demonstrated significant increases compared to T1 (uncoated control) ($p < 0.05$), showcasing the efficacy of the biopolymer coatings in retaining phenolics. This observation aligns with studies reporting the role of ECs in creating modified atmospheres, thereby delaying senescence and inhibiting enzymatic browning (Zhuang et al., 2011). Statistical analysis confirms the differences between treatments by day 14, where T7 had the highest phenolic content (2.91 mg GAE g^{-1} FDW) (D), significantly surpassing the control T1 ($p < 0.05$). This suggests that some treatments may enhance the release of bound polyphenols during storage while preventing their degradation or stabilising them during storage, which is consistent with findings by Lima et al. (2022). TPC also increased in T3 and T5, further supporting the role of antioxidants in prolonging the shelf life and nutritional quality of OFSP. . Previous studies suggest that polyphenols in uncoated produce are more susceptible to degradation through reactions with reactive oxygen species (ROS) during senescence (Jajic et al., 2015).

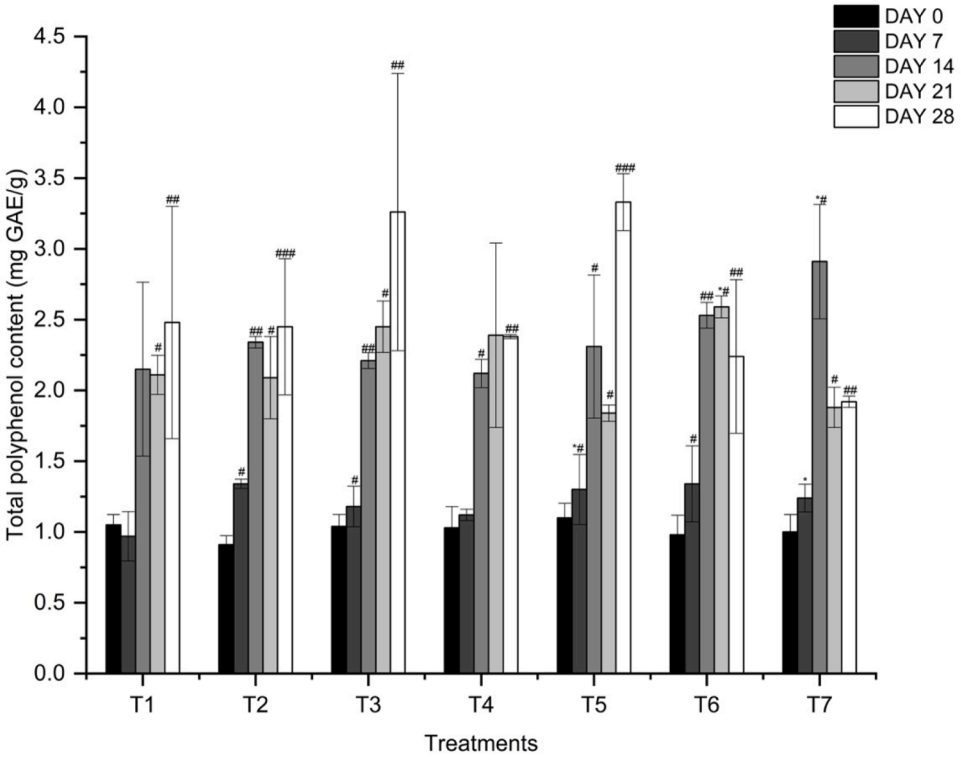

Fig. 3. Total Phenolic Content of Orange-Fleshed Sweet Potatoes (OFSP) During a 28-Day Storage Period Across Various Treatments.
This figure displays the total phenolic content (measured in mg GAE g^{-1} of the sample) of OFSP tuber samples subjected to seven different treatments, including an uncoated control. The x-axis represents the various treatments, while each bar corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the total phenolic content in mg GAE g^{-1} of the dry sample (FDW). Each treatment is represented by distinct bars for different analysis days, highlighting the variations in phenolic compound preservation. Error bars represent standard deviations and are marked where applicable. For the statistical analysis, Values in the same treatment group (with respect to control, T1) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by $^{\#}$, $^{\#\#}$, $^{\#\#\#}$, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

By day 21, T3 and T6 achieved TPC values of 2.45 ± 0.18 and 2.59 ± 0.08 mg GAE g^{-1} FDW, respectively, indicating stable phenolic retention compared to earlier days and the control, and demonstrating significant differences within treatments ($p < 0.05$). This stability suggests that the coatings effectively preserved polyphenols, likely due to the synergistic effects of antioxidants like chitosan and ascorbic acid, which protected against oxidative stress (Marghmaleki et al., 2020). These findings are consistent with studies showing that ECs can delay the enzymatic degradation of phenolics by scavenging reactive oxygen species (ROS) (Sen and Chakraborty, 2011). On day 28, T5 displayed the highest TPC (3.33 ± 0.20 mg GAE g^{-1} FDW), followed closely by T3 at 3.26 ± 0.98 mg GAE g^{-1} FDW, with both treatments showing significant differences from the control (Cb and Ca), suggesting that certain coatings may enhance polyphenol bioavailability during extended storage. The enhanced phenolic content observed in these treatments may be due to the release of bound phenolics or increased bioavailability over prolonged storage as reported by Chung and Moon, 2008. Conversely, T7 experienced a decline in TPC to 1.92 ± 0.04 mg GAE g^{-1} FDW, possibly due to polyphenol degradation linked to increased exposure to oxidative stress and PPO activity (Piechowiak and Skóra, 2023; Jajic et al., 2015). Furthermore, it suggests that the coating's protective capacity reduces as storage progresses. Overall, T3 and T5 demonstrated superior efficacy in maintaining phenolic content throughout storage by enhanced oxidative protection, highlighting the importance of EC formulations to enhance the postharvest quality and health benefits of OFSP tubers.

3.2.2. *Profiling and analysis of individual phenolic compounds (IPC)*

The systematic evaluation of the phenolic profile in OFSP across various EC treatments over a 28-day storage period reveals significant variations in individual polyphenolic content, which directly influences the nutritional retention and antioxidant potential of this nutritional tuber (Table 3). The analysis identified several key phenolic compounds, including derivatives of chlorogenic acid, caffeic acid, and their isomers, all of which are well-documented for their potent antioxidant properties and contributions to the nutritional value of OFSP (Alam, 2021). In particular, T3 exhibited exceptional efficacy in enhancing the retention of 3-CQA (3-caffeoylquinic acid), peaking at 1.72 ± 1.18 mg/ 100 g on day 28 ($p < 0.05$), a significant increase from the baseline concentration of 0.51 ± 0.12 mg/ 100 g recorded on day 0. This substantial increase in T3 suggests that this particular coating is highly effective at preserving this crucial polyphenol during storage. In addition to 3-CQA, T3 also significantly enhanced the levels of 4-CQA (4-caffeoylquinic acid), which reached a peak concentration of 42.11 ± 2.11 mg/ 100 g by day 21 ($p < 0.05$). This finding is particularly relevant as it underscores the role of caffeoylquinic acids in antioxidant activity, corroborating previous studies conducted by Teow et al. (2006) that emphasised the importance of these compounds in promoting health benefits through diet. In contrast, treatment T2 experienced a significant decline in 4-CQA levels by day 28, recorded at 28.34 ± 9.27 mg/ 100 g ($p < 0.05$), illustrating the variability and effectiveness of different coating treatments. Notably, while caffeic acid levels were highest in T1 at day 0 (1.60 ± 0.84 mg/ 100 g), all treatments exhibited a significant decline by day 7 ($p < 0.05$), likely due to the compound's susceptibility to oxidative degradation, as outlined by Robards et al. (1999). Moreover, T4 demonstrated the highest values for both 3,4-diCQA and 3,5-diCQA on day 28, with concentrations of 10.32 ± 8.97 mg/ 100 g ($p < 0.05$) and 56.29 ± 36.15 mg/ 100 g ($p < 0.05$), respectively, indicating its effectiveness in preserving specific polyphenolic compounds.

These findings collectively illustrate the critical influence of EC compositions on the stability of phenolic compounds during storage and the need to optimise coating formulations for OSFP. Notably, T7 which incorporates glycerol and LEO, is speculated to improve the barrier properties of the EC, thereby enhancing polyphenol retention (Marghmaleki et al., 2020; Yaashikaa et al., 2023). The hygroscopic nature of glycerol plays a significant role in moisture retention, enhancing the physical properties of the coatings, as supported by

Table 3
Individual Polyphenol Content (mg/100 g) of Orange-Fleshed Sweet Potatoes (OFSP) Across Different Chitosan-based EC Treatments.

IPC	Day 0	Day 7	Day 14	Day 21	Day 28
3-CQA					
T1	0.60 ± 0.26	0.68 ± 0.36	1.42 ± 0.97	1.50 ± 0.38	1.05 ± 0.44$^{\#}$
T2	0.36 ± 0.13	0.56 ± 0.05	1.05 ± 0.02$^{\#}$	0.51 ± 0.26	0.85 ± 0.49$^{\#}$
T3	0.51 ± 0.12	0.61 ± 0.49$^{\#}$	0.86 ± 0.38	1.28 ± 0.06$^{\#}$	1.72 ± 1.18$^{\#\#}$
T4	0.17 ± 0.06	0.80 ± 0.20$^{\#\#}$	1.36 ± 0.21$^{\#\#}$	1.14 ± 0.97	1.59 ± 0.19$^{\#\#\#}$
T5	0.69 ± 0.29	0.80 ± 0.44	0.80 ± 0.25	0.82 ± 0.54	0.81 ± 0.32
T6	0.40 ± 0.09	0.63 ± 0.38$^{\#}$	0.38 ± 0.07	0.99 ± 0.12	0.94 ± 0.65$^{\#}$
T7	0.47 ± 0.33	0.72 ± 0.27	0.88 ± 0.12	0.81 ± 0.24*	0.74 ± 0.47
4-CQA					
T1	23.61 ± 3.97	27.35 ± 9.16$^{\#}$	39.27 ± 12.87	38.03 ± 11.97	36.52 ± 11.73$^{\#}$
T2	21.72 ± 7.26	24.03 ± 1.06	34.90 ± 2.71	22.99 ± 11.51	28.34 ± 9.27
T3	23.88 ± 1.32	22.81 ± 1.10	28.02 ± 7.99	42.11 ± 2.11$^{\#}$	40.54 ± 24.51$^{\#}$
T4	14.00 ± 3.94	26.85 ± 0.33	31.65 ± 2.04	41.44 ± 23.89	35.88 ± 3.08$^{\#\#}$
T5	27.92 ± 6.22	23.19 ± 6.48	26.61 ± 5.16	25.42 ± 4.49	35.74 ± 17.03
T6	20.93 ± 6.90	32.03 ± 9.64	25.05 ± 2.07	35.55 ± 10.37	35.24 ± 18.89$^{\#}$
T7	24.44 ± 10.03	22.87 ± 5.09	31.35 ± 0.91	26.48 ± 0.90	23.26 ± 5.38
CAFFEIC ACID					
T1	1.60 ± 0.84	0.20 ± 0.05	0.21 ± 0.21	0.46 ± 0.06	0.40 ± 0.09
T2	0.81 ± 0.19	0.15 ± 0.08$^{\#}$	0.44 ± 0.03	0.29 ± 0.08	0.43 ± 0.21
T3	0.58 ± 0.14	0.29 ± 0.19	0.36 ± 0.13	0.44 ± 0.11	0.30 ± 0.12
T4	0.52 ± 0.28	0.18 ± 0.03	0.34 ± 0.05	0.48 ± 0.17	0.55 ± 0.13
T5	1.56 ± 0.59	0.20 ± 0.15	0.27 ± 0.19	0.37 ± 0.17*	0.27 ± 0.05
T6	1.22 ± 0.11	0.25 ± 0.12	0.12 ± 0.15$^{\#}$	0.55 ± 0.09$^{\#}$	0.16 ± 0.20$^{\#\#}$
T7	0.94 ± 0.18	0.21 ± 0.12	0.41 ± 0.08	0.17 ± 0.07*$^{\#}$	0.20 ± 0.12$^{\#}$
3,4-diCQA					
T1	2.68 ± 0.48	2.67 ± 0.21	7.11 ± 4.87	8.07 ± 5.10	10.09 ± 7.11$^{\#\#}$
T2	3.02 ± 0.66	3.36 ± 0.42*	6.20 ± 2.65	2.46 ± 1.40	5.56 ± 2.84$^{\#}$
T3	1.86 ± 0.05	2.92 ± 1.05$^{\#\#\#}$	4.86 ± 1.67	5.71 ± 2.40	9.87 ± 6.81$^{\#\#}$
T4	1.09 ± 0.85	4.30 ± 0.08*$^{\#}$	5.94 ± 0.99$^{\#}$	10.32 ± 8.97	8.29 ± 3.24$^{\#\#}$
T5	3.38 ± 1.88	3.00 ± 1.39	4.22 ± 2.34	3.46 ± 0.09	4.23 ± 2.83
T6	2.22 ± 1.17	5.75 ± 3.67$^{\#}$	1.94 ± 0.22	3.62 ± 0.92	7.60 ± 5.76$^{\#}$
T7	3.95 ± 2.87	2.60 ± 1.94	5.26 ± 0.05	3.84 ± 2.38	3.22 ± 0.89
3,5-diCQA					
T1	18.87 ± 0.39	24.36 ± 8.77$^{\#\#\#}$	47.75 ± 25.57	48.03 ± 0.82$^{\#\#\#}$	49.99 ± 29.73$^{\#\#}$
T2	20.85 ± 0.46*	27.21 ± 4.94$^{\#\#\#}$	48.33 ± 8.55$^{\#}$	25.35 ± 15.60*	38.35 ± 3.12$^{\#\#\#}$
T3	18.41 ± 0.46	27.54 ± 2.78$^{\#\#\#}$	37.10 ± 7.69$^{\#}$	45.19 ± 3.34$^{\#}$	49.84 ± 29.73$^{\#\#}$
T4	12.07 ± 4.50	26.42 ± 1.13	45.75 ± 1.63$^{\#}$	56.29 ± 36.15	45.45 ± 4.61$^{\#\#}$
T5	26.87 ± 10.49*	24.19 ± 10.05	30.81 ± 9.62	27.73 ± 3.39***	50.86 ± 19.92$^{\#}$
T6	19.25 ± 5.10	31.24 ± 14.45$^{\#}$	48.44 ± 7.67$^{\#}$	31.45 ± 3.37*	30.89 ± 17.99

(*continued on next page*)

Table 3 (*continued*)

IPC	Day 0	Day 7	Day 14	Day 21	Day 28
T7	25.09 ± 11.21	23.97 ± 5.62	27.27 ± 1.82	31.29 ± 1.02***	23.86 ± 5.67
4,5-diCQA					
T1	0.28 ± 0.03	0.38 ± 0.18$^{\#\#}$	1.09 ± 0.59	2.50 ± 1.02	1.66 ± 0.83$^{\#\#}$
T2	0.22 ± 0.06	0.90 ± 0.18*$^{\#\#\#}$	2.32 ± 0.92*$^{\#}$	1.20 ± 0.88	2.73 ± 0.72$^{\#\#\#}$
T3	0.18 ± 0.05	0.68 ± 0.40$^{\#\#}$	1.34 ± 0.60$^{\#}$	1.96 ± 0.10$^{\#\#}$	6.55 ± 6.43$^{\#\#}$
T4	0.27 ± 0.10	0.66 ± 0.08$^{\#}$	0.68 ± 0.20	1.51 ± 0.66	1.56 ± 0.17$^{\#\#}$
T5	0.39 ± 0.16*	0.98 ± 0.78*$^{\#\#}$	1.62 ± 1.01	0.64 ± 0.23	3.09 ± 2.13$^{\#\#}$
T6	0.31 ± 0.20	1.21 ± 0.86$^{\#\#}$	1.37 ± 0.19$^{\#}$	1.04 ± 0.18	2.01 ± 1.67$^{\#}$
T7	0.42 ± 0.41	0.39 ± 0.22	1.34 ± 0.32	0.55 ± 0.39*	0.96 ± 0.50
CHLOROGENIC ACID ISOMER					
T1	3.01 ± 0.49	3.50 ± 0.66	3.11 ± 3.04	5.11 ± 1.03	4.09 ± 0.18$^{\#}$
T2	2.46 ± 0.44	4.02 ± 0.74$^{\#}$	4.25 ± 0.14$^{\#}$	5.44 ± 2.93*	6.31 ± 3.09***$^{\#\#\#}$
T3	2.45 ± 0.46	4.28 ± 1.99$^{\#\#}$	4.33 ± 1.62	7.06 ± 0.38$^{\#}$	6.38 ± 4.36$^{\#}$
T4	1.34 ± 0.23	3.58 ± 0.40$^{\#\#}$	5.82 ± 0.92$^{\#\#}$	4.39 ± 0.46$^{\#}$	5.96 ± 0.63*$^{\#\#\#}$
T5	2.71 ± 0.76	3.98 ± 1.69$^{\#}$	4.76 ± 1.98	5.02 ± 3.36	8.46 ± 3.50**$^{\#\#}$
T6	2.44 ± 0.09	3.49 ± 0.57$^{\#\#}$	2.60 ± 0.84	4.76 ± 0.56$^{\#}$	4.57 ± 2.19$^{\#\#}$
T7	2.18 ± 0.36	3.93 ± 1.21$^{\#\#}$	4.26 ± 1.15	3.15 ± 0.43*	3.64 ± 1.23$^{\#}$

This table shows the concentrations of individual polyphenols, including 3-CQA, 4-CQA, Caffeic Acid, 3,4-diCQA, 3,5-diCQA, 4,5-diCQA, and Chlorogenic Acid Isomers in OFSP samples subjected to various treatments. CQA refers to caffeoylquinic acid, and diCQA refers to di-caffeoylquinic acid. Values in the same treatment group (with respect to control, T1) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by $^{\#}$,$^{\#\#}$, $^{\#\#\#}$, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

Paudel et al. (2023). The efficacy of chitosan-based coatings combined with bioactive additives in preserving key phenolic compounds such as 3-CQA, 4-CQA, and 3,5-diCQA suggests a protective barrier function against oxidative stress, ultimately extending the shelf life of OFSP (Wang and Gao, 2012; Zam, 2019; Makori et al., 2020). These insights provide a valuable foundation for optimising postharvest management strategies, contributing to enhanced nutritional quality and a broader understanding of phenolic retention dynamics under varying storage conditions.

3.2.3. *Antioxidant capacity measurement by TEAC assay*

In recent years, ECs incorporated with bioactive compounds have gained traction as a strategy to optimise fresh food quality by improving nutritional value and shelf life, thereby increasing consumer acceptance (Nunes et al., 2023). The results of TEAC analysis (Fig. 4) revealed dynamic changes in antioxidant capacity over a 28-day period across the seven treatments. Initially, all samples exhibited similar Trolox concentrations, ranging from 0.025 to 0.038 mmol g-1(FDW). This initial homogeneity highlights the baseline antioxidant levels in OFSP, which are influenced by intrinsic factors such as cultivar and growth conditions (Wang and Gao, 2012). By day 7, several treatments (T2, T5, T6, and T7) showed a marked increase in Trolox levels, particularly T5, which experienced a 66.67 % rise in concentration. The highest concentration was recorded in T7 samples on day 14, with a concentration of 0.076 ± 0.01 mmol g^{-1}, indicating that this combination of EC can effectively enhance antioxidant activity in OFSP. The incorporation of ascorbic and citric acids into coating formulations has proven effective in enhancing the nutritional value, colour, and antioxidant potential of fresh-cut mango cubes (Robles-Sánchez et al., 2012b). The presence of these organic acids is crucial, as they can scavenge free radicals and inhibit oxidative degradation of phenolic compounds, thereby contributing to overall antioxidant capacity (Zhang et al., 2019).

In contrast, the uncoated samples (T1) consistently showed lower concentrations throughout the observation period, suggesting that without a protective barrier, OFSP cannot retain antioxidants over extended storage periods. This finding aligns with existing literature that emphasises the importance of coatings in preserving the antioxidant properties of fresh produce (Caleb et al., 2012; Lima et al., 2022). The peak observed on day 14 in all samples was followed by a decline on day 21, likely reflecting the onset of antioxidant degradation or the depletion of substrates necessary for sustained antioxidant activity. The dynamic changes in antioxidant capacity can be attributed to various factors, including enzymatic activity, storage temperature, and moisture levels (Lima et al., 2022). Although there was a slight recovery in Trolox levels by day 28, the concentrations remained below the peak achieved on day 14. By the final observation on day 28, T3 and T5 reached the highest concentrations of 0.038 mmol g^{-1} and 0.046 mmol g^{-1}, respectively. These findings are consistent with other studies investigating the preservation of *Dimocarpus longan* using chitosan/nano-silica films, which significantly reduced the rate of vitamin C loss and helped mitigate browning and weight loss (Chung and Moon, 2008; Shi et al., 2013). Similarly, research on Jujube preservation using chitosan films (Yu et al., 2012b) and a combination of chitosan and 1-methylcyclopropene (Li et al., 2011; Cheng et al., 2020) demonstrated comparable benefits in maintaining antioxidant levels and overall fruit quality. Statistical analysis using the Tukey HSD test confirmed significant differences ($P < 0.05$) in Trolox concentrations across different days within the same treatment and between different treatments on the same day (Fig. 4). These results emphasise the critical role of treatment type and timing in influencing antioxidant levels in OFSP, underscoring the need for further exploration into the formulation of coatings that not only maintain antioxidant capacity but also synergistically enhance the bioactive properties of the produce over prolonged storage (Kawhena et al., 2021).

3.2.4. *Beta-carotene quantification and its impact on nutritional quality*

Beta-carotene is an essential bioactive compound present in OFSP that contributes significantly to its overall nutritional value, and colour and serves as a vital source of Vitamin A (Islam et al., 2015). To assess the retention of β-carotene in the treated OFSP samples, HPLC analysis was performed over a 28-day period. The results presented in Fig. 5, depict significant variability in retention of β-carotene depending on the EC treatment and duration of storage. Initially, β-carotene concentrations ranged from 0.56 ± 0.07 mg g^{-1} to 0.70 ± 0.00 mg g^{-1} FDW.

Essential oils possess antioxidant and antimicrobial properties, making them effective edible coating additives that can slow carotenoid degradation (Emragi et al., 2021). The incorporation of bioactive compounds like EOs into ECs has been shown to enhance the preservation of carotenoids by forming a barrier that limits oxygen exposure, thus reducing oxidative degradation (Robards et al., 1999). As the storage period progressed to day 14, T2 and T7 distinguished themselves by significantly increasing their β-carotene concentrations to 0.74 ± 0.03 mg g^{-1} and 0.73 ± 0.02 mg g^{-1}, respectively. This suggests that certain treatments not only prevent the loss of β-carotenoids but may also enhance β-carotene stability or promote its synthesis over time, potentially through the modulation of enzymatic activity and the minimisation of oxidative stress (Chung and Moon, 2008). On day 28, T1 exhibited the lowest concentration (0.60 ± 0.04 mg g^{-1}), indicating that the absence of a protective barrier may have led to increased moisture loss and ongoing post-harvest metabolic activities that accelerated β-carotene degradation. This finding underscores the importance of effective coatings or treatments to inhibit degradative processes, as previous studies have indicated that uncoated produce is significantly more susceptible to moisture loss and quality deterioration (Kawhena

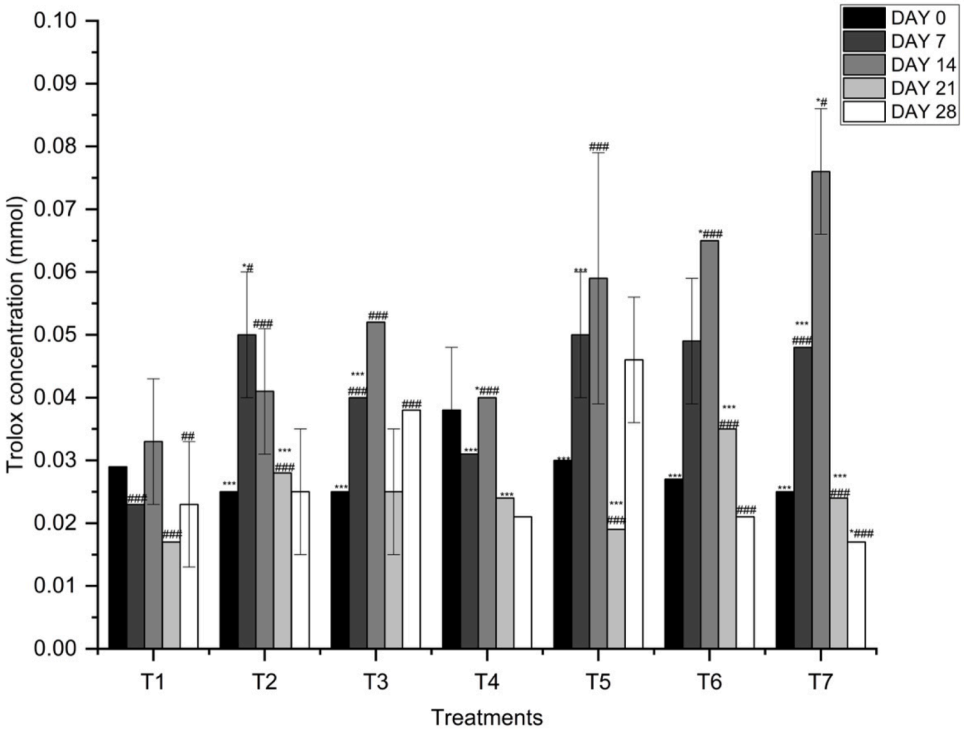

Fig. 4. Trolox Equivalent Antioxidant Capacity (TEAC) of Orange-Fleshed Sweet Potatoes (OFSP) Over a 28-Day Storage Period Across Various Treatments:. This figure presents the Trolox Equivalent Antioxidant Capacity (TEAC) values of OFSP tuber samples subjected to seven different treatments, including an uncoated control. The x-axis represents the various treatments, while each bar corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the TEAC values, expressed as mM TE g^{-1} dry sample (FDW). Each treatment is depicted by distinct bars for different analysis days, showing the changes in antioxidant capacity over time. Error bars represent standard deviations, and statistically significant differences are noted where applicable. Values in the same treatment group (with respect to control, T1) denoted either by $^{*, **, ***}$, and values across different observation days (with respect to day 0) denoted by $^{\#, \#\#, \#\#\#}$, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

et al., 2021). By the conclusion of the storage period, T2, T4, T5, and T7 demonstrated significant increases in β-carotene concentrations, with increments of 4.37 %, 25.35 %, 10.71 %, and 26.19 %, respectively.

The findings from the colour analysis of OFSP tubers closely align with the trends observed in β-carotene retention, highlighting how various treatments impact both visual appeal and nutritional quality. β-carotene contributes directly to the yellow-orange hue of OFSP, making the b* parameter a good indicator of its presence. For instance, T2 and T7, which showed increased β-carotene concentrations to 0.740 ± 0.03 mg g^{-1} and 0.732 ± 0.02 mg g^{-1} by day 14, also maintained higher b* values, reflecting richer yellowness early in storage. This suggests that the EOs in these treatments play a dual role by preserving both the visual appeal and the nutritional content of OFSP through antioxidant properties (Robards et al., 1999). A similar trend is observed with T7, where high final β-carotene levels correlate with stable hue angles (h°), indicating sustained colour vibrancy and pigment preservation. Meanwhile, T3's moderate colour values in redness (a*) by day 28 align with a recovery in β-carotene content, suggesting that certain treatments can mitigate degradation over time. This correlation between β-carotene and colour parameters, such as b* and C*, reinforces the importance of effective ECs in maintaining both the appearance and nutrient levels of OFSP during storage. These observations demonstrate that visual assessments, like the CIELAB scale, provide valuable insight into the preservation of bioactive compounds, offering a non-invasive method to monitor the quality of stored produce.

T7 emerged as the most effective treatment method (0.72 ± 0.09 mg g^{-1}), closely followed by T4 (0.72 ± 0.07 mg g^{-1}) offering superior long-term protection, thus contributing to the extension of shelf life and preservation of nutritional quality. These findings are supported by comparative analyses presented in Fig. 5, which illustrate significant differences between treatments and storage times at a $p < 0.05$ level. While this study demonstrates the effectiveness of specific treatments in retaining β-carotene content, other research indicates that storage conditions, particularly temperature, also play a crucial role in carotenoid stability. For instance, storing tubers at lower temperatures, such as 5 °C, rather than 20 °C, has been shown to better preserve carotenoids due to the high degree of unsaturation in carotenoid pigments, making them susceptible to degradation at higher temperatures (Mudyantini et al., 2023). This suggests that optimising storage conditions in conjunction with appropriate treatments could further enhance β-carotene retention in OFSP. The interaction between temperature and bioactive ECs could represent an effective strategy for maintaining the nutritional quality and sensory properties of OFSP during storage.

3.3. Microbiological safety and edible coating efficacy

3.3.1. Microbial inhibition and preservation by chitosan-based edible coatings

Microbial growth poses a significant challenge to maintaining the post-harvest quality and safety of OFSP tubers, contributing to reduced shelf life, diminished marketability, and decreased consumer appeal (Chuang, 2011). This study evaluated the effectiveness of various chitosan-based ECs, with and without essential oils and antioxidant organic acids, in controlling microbial growth over a 28-day storage period. Microbial loads were measured as colony-forming units (CFU) on selective agar media, including Plate Count Nutrient Agar (PCNA), MRS Agar (MRSA), MacConkey Agar (MAC), and Potato Dextrose Agar (PDA), with the results presented in Figs. 6A and 6B.

The inclusion of LEO was emphasised due to its documented antimicrobial properties (Burt, 2004; Muñoz-Tebar et al., 2023). Results showed that chitosan-based ECs, particularly treatments T5 and T7, significantly inhibited microbial growth compared to the uncoated

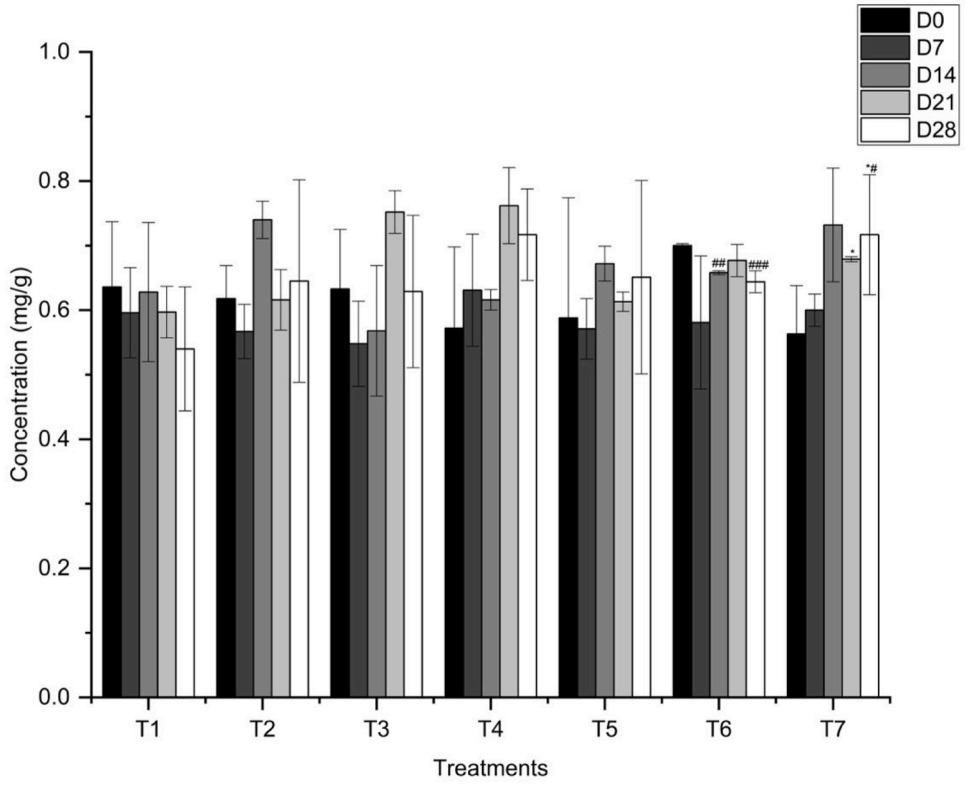

Fig. 5. Beta-Carotene Content of Orange-Fleshed Sweet Potatoes (OFSP) During a 28-Day Storage Period Across Various Treatments.
This figure illustrates the β-carotene content of OFSP tuber samples subjected to seven different treatments, including an uncoated control. The x-axis represents the various treatments, while each bar corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the β-carotene content, measured in mg β-carotene g^{-1} dry sample (FDW), showing the variations in retention across different treatments over time. Error bars represent standard deviations, and statistically significant differences are noted where applicable. Values in the same treatment group (with respect to control, T1) denoted by *, and values across different observation days (with respect to day 0) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by #, ##, ###, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

control (T1). For instance, on PCNA, T5 saw an increase from 1.72 ± 0.73 $\log_{10}$ CFU g^{-1} on day 0 to 2.78 ± 1.45 $\log_{10}$ CFU g^{-1} by day 28, while T7 increased from 1.66 ± 0.31 $\log_{10}$ CFU g^{-1} to 2.57 ± 0.17 $\log_{10}$ CFU g^{-1}. In contrast, the uncoated control (T1) reached 4.9 ± 0.86 $\log_{10}$ CFU g^{-1}, underscoring the antimicrobial efficacy of the chitosan-based ECs. This reduction in microbial counts is attributed to the synergistic antimicrobial properties of chitosan and LEO, known for disrupting microbial cell membranes, thus inhibiting growth (Burt, 2004; Muñoz-Tebar et al., 2023). Chitosan and LEO have been shown to effectively prevent mesophilic spoilage by disrupting cell walls, contributing to the extended shelf life of the samples through a robust barrier against bacterial and fungal proliferation (Yan et al., 2021).

3.3.2. *Mesophilic bacterial growth and its implications*

Mesophilic bacterial counts observed on PCNA offer key insights into the ability of ECs to control spoilage microorganisms. The control treatment, T1, demonstrated the highest bacterial count of 4.9 ± 0.86 $\log_{10}$ CFU g^{-1} by day 28, indicating substantial bacterial proliferation in the absence of antimicrobial interventions. This is in stark contrast to the results from the treatments with chitosan-based ECs. T5, containing chitosan and LEO, showed bacterial counts rising from 1.72 ± 0.73 $\log_{10}$ CFU g^{-1} on day 0 to 2.78 ± 1.45 $\log_{10}$ CFU g^{-1} by day 28, and T7, with similar treatment compositions, maintained even lower counts of 2.57 ± 0.17 $\log_{10}$ CFU g^{-1} by day 28. These findings align with previous studies, where chitosan and EOs have been shown to exhibit strong antimicrobial activity against mesophilic bacteria, likely due to the disruption of bacterial cell walls, leading to cell death (Burt, 2004; Muñoz-Tebar et al., 2023). The findings reflect the antimicrobial properties of the ECs, particularly in their ability to significantly lower mesophilic bacterial counts compared to the control ($p < 0.05$), as demonstrated by T5 and T7. This suggests that both the type of ECs and storage duration have a profound impact on bacterial growth (Yan et al., 2021), underscoring the importance of selecting appropriate formulations for the preservation of perishable products.

3.3.3. *Lactic acid bacteria and gram-negative bacterial growth on selective media*

Lactic acid bacteria (LAB) count across all treatments, including the uncoated control, remained below detectable levels (BDL) on MRSA, indicating that conditions during the storage period were not favourable for LAB proliferation. The absence of statistically significant differences between treatments further supports this observation. The consistently low LAB presence suggests that the environmental conditions and coatings used may have contributed to reducing spoilage microorganisms, thereby potentially extending the shelf life of the orange-fleshed sweet potatoes (Panda et al., 2007).

Similarly, Gram-negative bacterial growth on MAC was also BDL across all treatment groups. As a result, no statistically significant conclusions could be drawn regarding the impact of treatments on this bacterial group. The suppression of both LAB and Gram-negative bacterial growth highlights the broad-spectrum efficacy of the chitosan-based edible coatings in inhibiting microbial proliferation. This microbial inhibition is critical for enhancing the safety and quality of OFSP during extended storage periods (Moon et al., 2020).

3.3.4. *Fungal growth analysis on potato dextrose agar (PDA)*

Fungal growth, as measured on PDA, further highlights the efficacy of chitosan-based ECs in controlling fungal contamination. The control

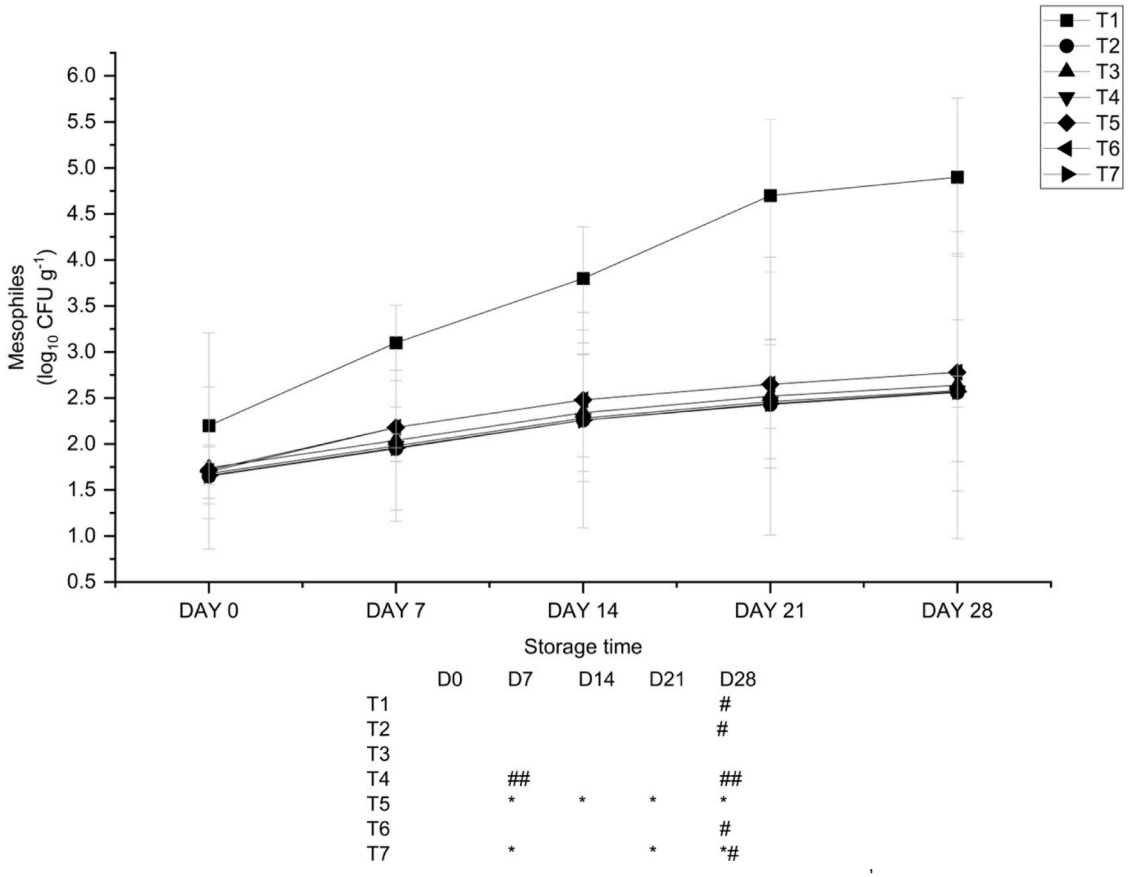

Fig. 6A. Growth of Mesophilic Bacteria (log_{10} CFU g^{-1}) in Orange-Fleshed Sweet Potatoes (OFSP) Over a 28-Day Storage Period Across Various Treatments. This figure shows the growth of mesophilic bacteria, expressed as log_{10} CFU g^{-1}, in OFSP tuber samples subjected to seven different treatments, including an uncoated control. Bacterial growth was measured using Plate Count Nutrient Agar (PCNA). The x-axis represents the various treatments, while each data point corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the bacterial count in log_{10} CFU g^{-1}. Error bars represent standard deviations, and statistically significant differences are noted where applicable. Alphabets representing statistics are tabulated below the graph. Values in the same treatment group (with respect to control, T1) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by #, ##, ###, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

group, T1, exhibited the highest fungal growth, reaching 5.1 ± 1.47 log_{10} CFU g^{-1} by day 28, indicative of significant fungal proliferation. In comparison, T5, which started at 2 ± 1.54 log_{10} CFU g^{-1}, demonstrated the most effective control of fungal growth, culminating in a mean count of 2.8 ± 1.41 log_{10} CFU g^{-1} at day 28. Similarly, T7 exhibited fungal counts of 3.2 ± 0.48 log_{10} CFU g^{-1} by day 28, showing moderate growth inhibition but still significantly lower than the control ($p < 0.05$). The antifungal properties of chitosan and LEO are well-documented in the literature, particularly for their ability to disrupt fungal cell membranes, effectively reducing fungal contamination (Burt, 2004; Ali et al., 2014; Martins et al., 2014; Kawhena et al., 2021). This aligns with the current findings, where T5 and T7 significantly inhibited fungal growth compared to the control group ($p < 0.05$). Furthermore, the data support findings by Gago et al. (2020), which suggest that EOs can enhance the antifungal properties of chitosan-based coatings, further reinforcing the protective effect of these treatments in prolonging shelf life by reducing spoilage fungi.

3.3.5. Comparative efficacy of edible coating treatments on microbial control

A comparative analysis of the seven treatments on PCNA and PDA revealed that T5 and T7 were the most effective at controlling microbial growth. The control treatment (T1) consistently showed the highest microbial loads, with 4.9 ± 0.86 log_{10} CFU g^{-1} for bacteria and 5.1 ± 1.47 log_{10} CFU g^{-1} for fungi by day 28. In contrast, T5, containing chitosan and LEO, showed the lowest bacterial count of 2.78 ± 1.45 log_{10} CFU g^{-1} and fungal count of 2.8 ± 1.41 log_{10} CFU g^{-1}, while T7 showed comparable efficacy with bacterial counts of 2.57 ± 0.17 log_{10} CFU g^{-1} and fungal counts of 3.2 ± 0.48 log_{10} CFU g^{-1} by day 28. The statistical analysis confirms significant differences ($p < 0.05$) between the control group and the treated groups, particularly for T5 and T7, with respect to both bacterial and fungal growth, underscoring their superior performance. These findings are consistent with the antimicrobial effects of chitosan and EOs, as described in studies by Burt (2004), Ali et al. (2014), and Gago et al. (2020), where chitosan-based ECs combined with EOs were shown to effectively reduce both bacterial and fungal contamination over time. The synergistic antimicrobial effects observed in T5 and T7 can be attributed to the disruption of microbial and fungal cell membranes, resulting in decreased microbial viability (Burt, 2004; Martins et al., 2014). These results highlight the potential of chitosan-EO formulations as an effective strategy for extending the shelf life of perishable products, reinforcing previous research on the efficacy of chitosan and LEO as antimicrobial agents (Muñoz-Tebar et al., 2023; Yan et al., 2021).

4. Conclusion

In light of the study's findings, the use of chitosan-based edible coatings (ECs), particularly those enriched with lemongrass essential oil (LEO), demonstrates significant promise in extending the postharvest quality of orange-fleshed sweet potato (OFSP) tubers. Through a detailed analysis of various physical quality parameters, it was evident

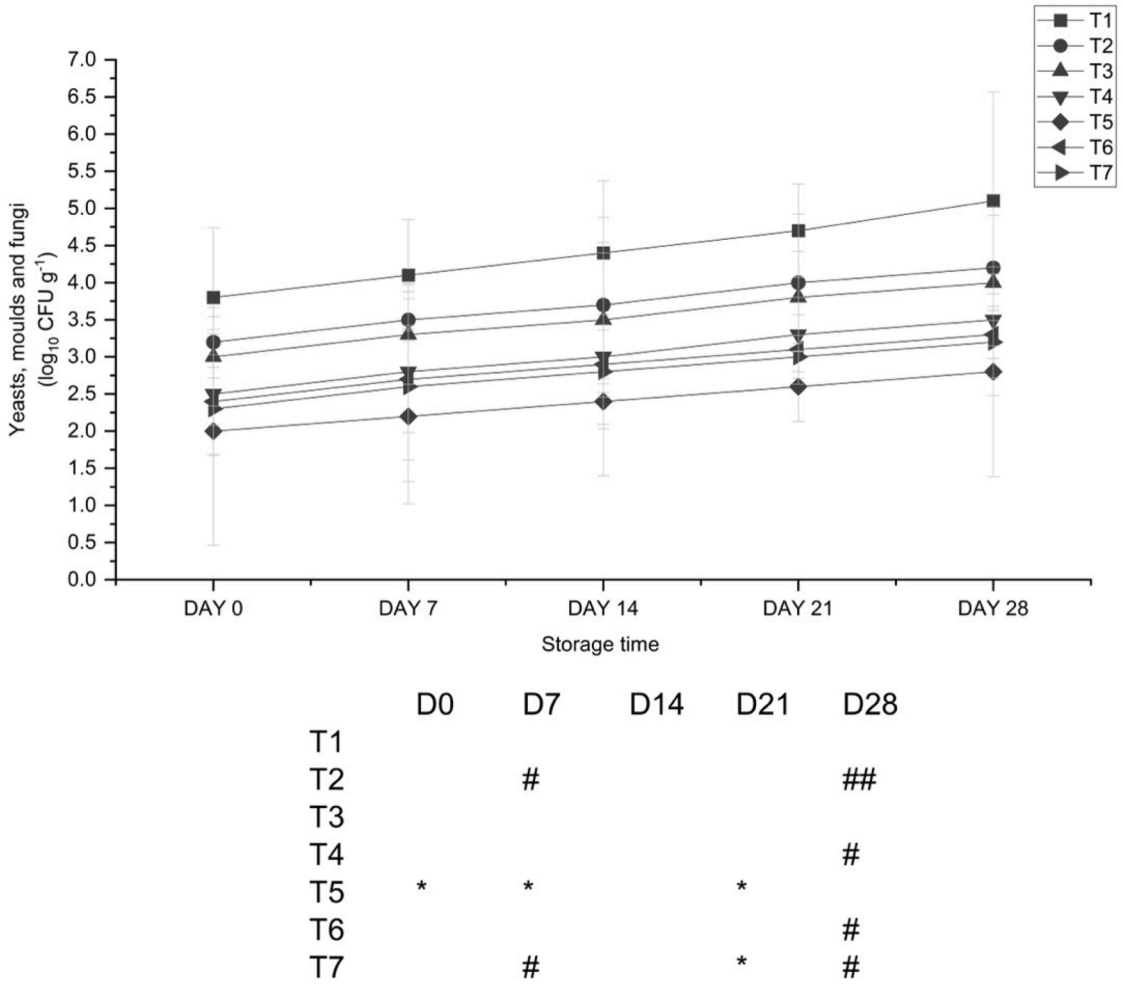

Fig. 6B. Growth of Moulds, Yeasts, and Fungi (log_{10} CFU g^{-1}) in Orange-Fleshed Sweet Potatoes (OFSP) Over a 28-Day Storage Period Across Various Treatments. This figure illustrates the growth of moulds, yeasts, and fungi, expressed as log_{10} CFU g^{-1}, in OFSP tuber samples subjected to seven different treatments, including an uncoated control. Fungal growth was measured using Potato Dextrose Agar (PDA). The x-axis represents the various treatments, while each bar corresponds to the analysis days throughout the 28-day storage period. The y-axis indicates the fungal count in log_{10} CFU g^{-1}. Error bars represent standard deviations, and statistically significant differences are noted where applicable. Alphabets representing statistics are tabulated below the graph. Values in the same treatment group (with respect to control, T1) denoted either by *, **,***, and values across different observation days (with respect to day 0) denoted by #, ##, ###, indicate a significant difference ($p < 0.05$, $p < 0.005$ and $p < 0.0005$ respectively) based on the Tukey HSD comparison test.

that these ECs effectively reduced weight loss and maintained colour stability and firmness, critical attributes of produce that determine both consumer acceptance and shelf-life. For instance, tuber weight loss was notably minimised by the chitosan-LEO formulation (T5), achieving a 5.65 % weight reduction compared to the 13.23 % seen in uncoated control (T1) by day 28. This result highlights the barrier properties of chitosan combined with EOs, which limit moisture loss by reducing water vapour transmission and minimising enzymatic reactions. Despite this, the diminished effectiveness after 14 days suggests a need for further optimisation to improve the long-term stability of the coating. Similarly, while colour measurements indicated a decline in lightness (L*) and chroma (C) across all treatments, chitosan-LEO coatings were particularly effective at delaying pigment degradation. This protective effect, likely due to the antioxidant properties of EOs, preserved key bioactive compounds, such as carotenoids, which are essential for the tuber's nutritional and visual appeal. The ability of these ECs to maintain firmness—with T5 showing a 26.20 % increase in firmness—further underscores their potential to hinder moisture loss and enzymatic breakdown, both of which are central to postharvest deterioration. These results suggest that chitosan-EO EC formulations can mitigate key postharvest challenges, although further optimisation in coating composition and application methods may be necessary to achieve long-term efficacy.

Beyond the physical quality attributes, the study also focused on the bioactive metabolite retention and antioxidant properties of the coated OFSP tubers. The quantification of total phenolic content (TPC), a key indicator of produce quality, revealed that the chitosan-LEO coatings not only preserved but enhanced the antioxidant capacity of the tubers over the storage period. For instance, by day 28, T5 exhibited the highest TPC (3.33 mg GAE g^{-1} FDW), surpassing all other treatments, including the control, which suggests that the gas-barrier properties of chitosan and the radical-scavenging activity of EOs effectively protected the tubers from oxidative stress. This enhancement in antioxidant capacity is particularly significant, as it contributes to the nutritional value and shelf-life of OFSP tubers, both of which are key concerns in the context of global food security and sustainability. Furthermore, the beta-carotene content, vital for the vitamin A supply, was also better preserved in chitosan-coated samples, with T2 and T7 showing significant increases by day 14. The antimicrobial properties of chitosan-EO formulations, particularly in treatments T5 and T7, were further substantiated by the significant reduction in microbial growth, with bacterial and fungal counts remaining well below those of the uncoated control (T1). This microbial inhibition is critical, as post-harvest spoilage is largely driven by microbial contamination, and the study supports the

hypothesis that chitosan-LEO coatings disrupt microbial cell membranes, thus extending the microbiological safety of stored produce. Overall, while the study provides compelling evidence for the potential of chitosan-EO edible coatings, future research should address their long-term stability, optimisation of coating formulation, refining essential oil type and concentrations, and their impact on sensory qualities to ensure both efficacy and consumer acceptance in real-world applications. Thus, edible coatings, by extending shelf life and preserving the quality of perishable crops, offer a sustainable solution to food security challenges and contribute to achieving global nutritional and food security goals.

CRediT authorship contribution statement

Rohan Rama Krishnan: Writing – original draft, Methodology, Investigation, Formal analysis. **Keya Himanshu Patel:** Writing – original draft, Methodology, Investigation, Formal analysis. **Abdulhakeem Dapo Olasupo:** Validation, Methodology, Investigation. **Chikere Nkwonta:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Islamiyat Folashade Bolarinwa:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Moruf Olanrewaju Oke:** Supervision, Project administration, Funding acquisition, Conceptualization. **Xiafei Xu:** Writing – original draft, Methodology, Investigation. **Jingwen Wu:** Writing – original draft, Methodology, Investigation. **Andrea Yong:** Writing – original draft, Methodology, Investigation, Formal analysis. **Ping Li:** Methodology, Investigation, Formal analysis. **Ziqi Liang:** Methodology, Investigation, Formal analysis. **Idolo Ifie:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Idolo Ifie reports financial support was provided by Innovate UK KTP 22–23 R3ME [Project Number 10,048,462]. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2025.113956.

Data availability

No data was used for the research described in the article.

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