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Enhancing Mexican lime (*Citrus aurantifolia cv.*) shelf life with innovative edible coatings: xanthan gum edible coating enriched with *Spirulina platensis* and pomegranate seed oils

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Abstract

Background The Mexican lime (*Citrus aurantifolia* cv.), widely consumed in Iran and globally, is known for its high perishability. Edible coatings have emerged as a popular method to extend the shelf life of fruits, with xanthan gum-based coatings being particularly favored for their environmental benefits. This study aims to evaluate the effectiveness of an edible coating formulated from xanthan gum, enriched with *Spirulina platensis* (Sp) and pomegranate seed oil (PSO), in improving the quality and reducing the weight loss of Mexican lime fruit under conditions of 20 ± 2 °C and 50–60% relative humidity.

Results Based on the results, the application of coatings was generally effective in reducing fruit weight loss, with the least weight loss observed in the xanthan gum 0.2%+ *Spirulina platensis* extract (1%) treatment. Additionally, the levels of total phenols and flavonoids in the treated fruits exceeded those in the control group, with xanthan gum 0.2%+ *Spirulina platensis* extract (1%) and xanthan gum 0.2% exhibiting the highest concentrations of these compounds. The antioxidant capacity of the fruits was also enhanced by the coatings, surpassing that of the control group, with xanthan gum 0.2%+ *Spirulina platensis* extract (1%) achieving the highest levels. The treatments significantly suppressed the activity of the polyphenol oxidase (PPO) enzyme, with xanthan gum 0.2% demonstrating the most potent inhibitory effect. Furthermore, the treatments resulted in increased activities of catalase (CAT) and peroxidase (POD) enzymes compared to the control. Except for xanthan gum 0.2%+ pomegranate seed oil (0.05%), all treatments maintained the fruit's greenness (a*) more effectively than the control.

Conclusions Peel browning is a major factor contributing to the decline in quality and shelf life of lime fruit. The application of 0.1% and 0.2% xanthan gum coatings, as well as a combination of 0.2% xanthan gum and *Spirulina platensis* extract, significantly inhibited PPO activity and enhanced the activity of CAT and POD and phenolic compound in Mexican lime fruits stored at of 20 ± 2 °C for 24 days. Consequently, these treatments comprehensively

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preserved lime fruit quality by significantly reducing browning, maintaining green color, and preserving internal quality parameters such as TA, thereby enhancing both visual appeal and overall fruit quality.

Keywords Citrus, Postharvest quality, Coating, *Spirulina platensis*, Xanthan gum

Introduction

Mexican lime (*Citrus aurantifolia* cv.), celebrated for its nutritional benefits, is rich in vital components including citric acid, ascorbic acid, minerals, and flavonoids [1]. Despite the annual global production of limes hitting around 21 million tons, the industry faces significant post-harvest losses, which vary between 18% and 25% [2, 3]. A primary indicator of postharvest deterioration in limes is the loss of peel greenness, primarily attributed to chlorophyll degradation. Additionally, these fruits exhibit a significant rate of water loss following harvest. Notably, in tropical regions with high humidity and temperature, the shelf life of lime fruits is limited to approximately 6–9 days under ambient conditions [4]. To mitigate these losses, it is imperative to develop postharvest treatments that extend the shelf life of limes while maintaining their quality. This will ensure a reliable supply of fresh limes year-round, meeting the demands of both domestic processing and export markets [5]. The application of 5 µg/l nitric oxide was demonstrated to effectively preserve lime weight, firmness, ascorbic acid content, and chlorophyll, thereby prolonging lime shelf life [6]. In addition, studies have demonstrated that putrescine and salicylic acid treatments can effectively extend the shelf life of limes. Among these, putrescine, particularly at a concentration of 0.5 mM, was shown to be superior to salicylic acid in preserving lime peel color [5]. But these methods often have limitations, including high costs and potential health concerns associated with chemical residues. More recently, the use of edible coatings has emerged as a promising alternative.

Edible coatings present a sustainable method for reducing food waste by creating a protective barrier for fruits. Furthermore, these coatings possess the potential to enhance the visual appeal and taste of fruits, making them more appealing to consumers [7]. Xanthan gum, an exopolysaccharide synthesized by *Xanthomonas campestris* under unfavorable conditions. It is recognized as a safe food additive by regulatory agencies such as the Food and Drug Administration (FDA) [8]. Xanthan gum coatings have been shown to significantly improve the postharvest quality of guava fruits by modulating physiological and biochemical processes, thereby reducing decay, preserving bioactive compounds, and enhancing antioxidant enzyme activities [9]. While xanthan gum coatings offer significant benefits, excessive thickness can compromise texture. Therefore, careful calibration of concentration and innovative application techniques are essential for maximizing the advantages of xanthan gum coatings in fruit preservation. The combination of xanthan gum with lemongrass oil at 1.0% improved sensory quality and reduced spoilage in Kinnow mandarins, demonstrating that synergistic approaches can optimize coating performance [10]. Additionally, it has been reported that incorporating oleic acid into xanthan gum improved the quality of sapodilla fruit by enhancing firmness, increasing antioxidant capacity, and reducing weight loss.

Seaweeds and their extracts, rich in polysaccharides, polyphenols, antioxidants, and antimicrobial compounds, show great potential as edible coatings for preserving food quality and extending shelf life [11]. *Spirulina platensis*, a blue-green microalga, has been widely utilized in food and nutritional supplements due to its rich chemical composition, which includes phytohormones, antibacterial and antifungal properties, antioxidant compounds such as vitamins, phenolics, and pigments along with polyunsaturated fatty acids, minerals, and proteins [12]. In a previous study by [13], it was reported that a 1% concentration of *S. platensis* coating effectively slowed down color changes, maintained sugar levels, and preserved ascorbic acid content in carambola fruit. Another study conducted by [14] examined the use of a guar-based edible coating with *S. platensis* and *Aloe vera* extract on mangoes. The study found that spirulina-based coatings significantly preserved the firmness and increased bioactive compounds in fruits, extending their shelf life compared to uncoated ones.

Pomegranate seed oil is a valuable byproduct of the pomegranate industry, rich in bioactive compounds and fatty acids. The oil's high content of punicic acid and tocopherols contributes to its antioxidant properties and makes it suitable for various applications in food and pharmaceuticals [15]. Additionally, pomegranate seed oil was highlighted as a natural alternative to synthetic agents, improving the fruit's resistance to oxidation and microbial degradation [16]. Abundant in bioactive lipids, particularly the rare punicic acid, which constitutes a significant portion (74–85%) of its total fatty acid content, PSO is highly valuable for human nutrition [17]. PSO can serve as a natural additive to mitigate quality deterioration during storage while preserving the nutritional integrity of the product [18]. Edible coatings made with *Chlorella sp.* and PSO have been shown to enhance the quality of *Spondias tuberosa* fruit by preserving color, texture, and bioactive compounds during cold storage. The coated fruits ripened more slowly and retained both firmness and mass better than the uncoated controls [19]. It has been reported that a combination of

tamarind starch and PSO effectively improved the postharvest quality of guava fruit. This treatment significantly enhanced fruit luminosity, delayed color changes, reduced mass loss, and preserved firmness [20].

Despite the promising results demonstrated by various edible coatings in preserving the quality and extending the shelf life of fruits, the specific combination of Xanthan gum with *Spirulina platensis* and pomegranate seed oil has not been studied for postharvest treatment of fruits. While previous research has shown the efficacy of *Spirulina platensis* and PSO in other fruits, their combined effect within a xanthan gum coating for lime preservation remains unexplored. The primary goal is to formulate an innovative edible coating using xanthan gum enriched with *Spirulina platensis* and PSO. This coating aims to provide a sustainable and eco-friendly solution for extending the shelf life of Mexican lime fruits. The study seeks to rigorously assess the impact of the coating on key quality parameters of Mexican lime fruits during storage, including weight loss, color retention, phenolic compound preservation, and antioxidant system. By developing and validating this novel coating, the study aims to contribute to more sustainable postharvest management practices, reducing food waste and ensuring the year-round availability of high-quality Mexican limes for both domestic and export markets. Finally, the research seeks to advance scientific understanding of how bioactive edible coatings can be optimized for specific fruit types, potentially offering a new avenue for postharvest treatment strategies that can be applied to a variety of other fruits as well.

Materials and methods

The Mexican lime (*Citrus aurantifolia*) fruits utilized in this study were obtained from a commercial orchard situated in Hormozgan province, at approximately 57 °E longitude and 27 °N latitude, with an elevation of about 185 m above sea level. Harvesting was carried out at the mature green stage in accordance with standard technical guidelines. For the experiments, only fruits that were uniform in size, exhibited a mature green skin color, had a healthy appearance, and were free from mechanical damage were selected. Prior to testing, the selected fruits were thoroughly washed and disinfected by immersing them in water and a 0.05% sodium hypochlorite solution for one min.

Table 1 Experimental treatments and corresponding abbreviations for edible coatings

Treatment	Abbreviation
Control	Control
Xanthan gum 0.1% (w/v)	XG 0.1%
Xanthan gum 0.2% (w/v)	XG 0.2%
Xanthan gum 0.1%+ Pomegranate seed oil (0.05%) (w/v)	XG 0.1%+ PSO
Xanthan gum 0.2%+ Pomegranate seed oil (0.05%) (w/v)	XG 0.2%+ PSO
Xanthan gum 0.1%+ *Spirulina platensis* extract (1%) (w/v)	XG 0.1%+ SP
Xanthan gum 0.2%+ *Spirulina platensis* extract (1%) (w/v)	XG 0.2%+ SP

Coating and treatments

After preparing the xanthan gum edible coating at concentrations of 0.1% and 0.2% (w/v), the fruits were immersed in the treatment process for 5 min, as detailed in Table 1. The fruits were then allowed to air dry before being stored at 20±2 °C and 50–60% RH for 24 days.

Physiological responses

Overall visual acceptability (OVA)

The OVA assessment was conducted by a qualified team of five trained individuals with experience in evaluating fruit quality. To assess the overall appearance, color, and texture of the fruits, visual evaluations were conducted following the methodology described by [21]. The assessment was based on a 4-point scoring system. Evaluation criteria included fruit quality attributes such as freshness, greenness, peel glossiness, pitting, skin shriveling, and discoloration: Excellent (4): Fresh, firm, and high-quality fruits featuring a glossy peel. Such fruits display no signs of dehydration, skin shriveling, or discoloration. Good (3): These fruits are marketable and acceptable. They exhibit slight shriveling and softness but still maintain a satisfactory level of quality. Average quality (2). The fruits are not suitable for sale due to moderate symptoms of shriveling, dryness, and a loss of their green color. They are transitioning towards the browning, yet they remain edible despite these conditions. Poor quality (1): exhibiting severe symptoms of shriveling, over-ripeness, darkening of the peel color, and decay. These fruits are of very low quality and are deemed unsuitable for consumption.

Weight loss

Weight loss in lime fruits was measured by calculating the percentage reduction in mass from the initial to the final day of storage using a digital scale [22]:

$$PR = \frac{w_{initial} - w_{final}}{w_{initial}} \times 100 \quad (1)$$

Determination of the total phenolic content (TPC) and the total flavonoid content (TFC)

Compounds were extracted from fruit juice 500 mL by blending with 80% methanol and centrifuging at 4000 ×*g* for 10 min to separate solids and collect the supernatant rich in targeted compounds for analysis.

Total phenolic content was measured by mixing 0.3 mL of methanol extract with 1.2 mL of 7% sodium carbonate

and 1.5 mL of diluted Folin–Ciocalteu reagent, incubating the mixture at room temperature for 90 min, and then measuring the absorbance at 750 nm with a Cecil 2501 spectrophotometer [23].

Total flavonoid content was measured by mixing methanol extract with $AlCl_3$ and potassium acetate solutions, incubating for 30 min, and then measuring absorbance at 415 nm using a UV-visible spectrophotometer, using quercetin for calibration [24].

Determination of antioxidant activity

DPPH radical scavenging activity was measured by mixing DPPH in methanol with an extract, incubating for 40 min in the dark, and then measuring absorbance at 517 nm. The scavenging level was indicated by calculating the percentage of inhibition [25].

$$I_n\ (\%) = \frac{C_{control} - S_{sample}}{C_{control}} \times\ 100 \qquad (2)$$

The activity of antioxidant enzymes

The process of extracting and quantifying PPO activity was meticulously conducted in accordance with the methodological framework established by [26]. A 2.0 g sample was homogenized in a 20 mL phosphate buffer (pH 7) with 1 mM PEG and 4% PVPP, and kept in an ice bath to preserve enzyme activity. After centrifuging at 6000 rpm for 10 min at 4 °C to obtain crude PPO, the enzyme's activity was measured by mixing 80 µL of 0.5 M catechol with 100 µL of 0.05 M phosphate buffer (pH 6.5), incubating at 35 °C for 5 min, and monitoring absorbance changes at 420 nm with a spectrophotometer.

The determination and assay of POD activity were spectrophotometrically performed using a modified method based on the protocol described by [27]. A 2.0 g sample was homogenized with phosphate buffer (pH 6.5), PEG, and PVPP, centrifuged, and the supernatant used for a POD activity assay. The assay measured absorbance changes at 470 nm in a mixture of guaiacol, enzyme solution, and hydrogen peroxide at 15-second intervals using a spectrophotometer.

The evaluation of catalase (CAT) activity followed the method established by [28] with some modification. To initiate the experiment, a reaction mixture was prepared by combining 0.2 mL of enzyme extract with 50 mM Na_3PO_4 (pH 7.0) and 150 mL of 20 mM H_2O_2. The reaction between CAT and hydrogen peroxide caused a reduction in absorbance at 240 nm.

Fruit color determination

Color measurements were performed on the surface of the fruits, around the equatorial region. Sample colors were evaluated using the CIE Lab color space with a Chroma meter CR-400 by Konica, Tokyo, Japan. The CIE Lab includes three coordinates: L* (luminosity), a* (red-green axis), and b* (yellow-blue axis). L* values range from 0 (black) to 100 (white), a* indicates red or green presence, and b* signifies yellow or blue presence. Additional color characteristics like chromaticity (C*) and Hue angle (H°) were possibly assessed [29].

Determination of total soluble solids (TSS), titratable acidity (TA) and pH

The TSS content of fruit juice was measured using a digital refractometer, model DBR 95, at 25 °C, and expressed as a percentage. The pH of lime juice was determined with a pH meter, model HI93141, from HANNA, Portugal, calibrated with pH 7.0 and 4.0 buffer solutions. The titratable acidity was found by titration with a 0.1 M NaOH solution until pH 8.2, expressed as citric acid percentage [30].

Statistical analysis

In this research, a factorial experiment was carried out using a completely randomized design (CRD). The data obtained from the experiment were subjected to a comparative analysis using the LSD (Least Significant Difference) test at a statistical significance level of $p<0.05$. The statistical analysis was conducted using SAS software, version 9.4 and graphs were produced using GraphPad Prism software (GraphPad Software Inc., CA). PCA was conducted utilizing XLSTAT software, version 2020, developed by Addinsoft SARL and accessible at the website www.xlstat.com. The website https://www.bioinformatics.com.cn/en was utilized for hierarchical cluster analysis and Pearson correlation analysis.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

In agricultural and experimental research, statistical methods are crucial for comparing treatment effects through means and variances. Traditional unidimensional approaches may lack comprehensive insight when multiple factors are considered. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision-making (MCDM) method, provides a more holistic evaluation by concurrently assessing and ranking treatments based on their performance across all relevant criteria [31]. TOPSIS excels in consolidating multiple criteria into a unified ranking by assessing both positive and negative attributes of treatments. It measures the distance from ideal solutions to evaluate the closeness of each treatment to optimal performance, enabling a comprehensive analysis across all relevant parameters [32]. The TOPSIS method, focusing on proximity to the Positive Ideal Solution (PIS) and distance from the Negative Ideal Solution (NIS), was employed

to evaluate seven edible coatings across 17 parameters. Parameters were categorized into positive (e.g., L*, CAT) and negative criteria (e.g., a*, b*), each with equal weighting, to identify the most effective coatings for agricultural applications. This integrative approach adeptly addresses the complex interactions within agricultural systems, seeking an optimal trade-off solution (Fig. 1) [33].

Results

Overall visual acceptability (OVA)

As depicted in Fig. 2, a relatively diminished color alteration was observed in the applied treatments compared to the control group. The highest OVA and minimal discoloration were noted in the XG 0.1% and 0.2% treatments, as well as the XG 0.2% + SP treatment. However, the control treatment exhibited the lowest OVA, demonstrating pronounced fruit color alteration and desiccation.

Weight loss

In Fig. 3, it is evident that the applied coatings significantly prevented fruit weight loss after 24 days of storage at ambient temperature. In comparison to both the control group and the remaining interventions, XG 0.2+SP treatment showed the lowest weight reduction, and this difference was statistically significant.

Total phenols, flavonoids content and antioxidant capacity

Total phenol content decreased during storage, but all treatments, except PSO, were significantly higher than the control. The maximum total phenol content was observed in XG 2% and XG 2% + SP treatments (Fig. 4a).

Following 24 days of storage, there was a significant decrease in flavonoid content. However, the fruits that underwent treatment displayed elevated levels of flavonoids in comparison to those in the control group. Maximum and minimum total phenol were observed in XG 2% + SP and control, respectively (Fig. 4b).

Regarding antioxidant capacity, except for the fruits treated with XG 0.1+SP, which showed the highest antioxidant capacity, other treatments exhibited a decreasing trend through storage. At the end of the experiment, every treatment exhibited a notable increase when compared to the control group (Fig. 4c).

The activity of antioxidant enzymes

As shown in Fig. 5, PPO enzyme significantly increased at the end of the experiment in the control treatment, reaching levels of 97.9 U/mgFW, compared to the initial value of 62.6 U/mgFW. Nonetheless, across the other treatments, there was no notable differences in enzyme activity when compared to the initial day of storage (Fig. 5a).

In most treatments, POD enzyme activity exhibited an increase, except in the control. After 24 days of storage, it was observed that enzyme activity had reached its peak in the XG 0.2%+SP treatment, followed by the XG 0.2% treatment (Fig. 5b).

Except for the control, XG 0.2%+PSO treatment, which remained relatively stable during storage, the other treatments showed a significant increase. At the end of the experiment, the maximum CAT enzyme activity was observed in the XG 0.2% (367 U/mgFW) and XG 0.2% +

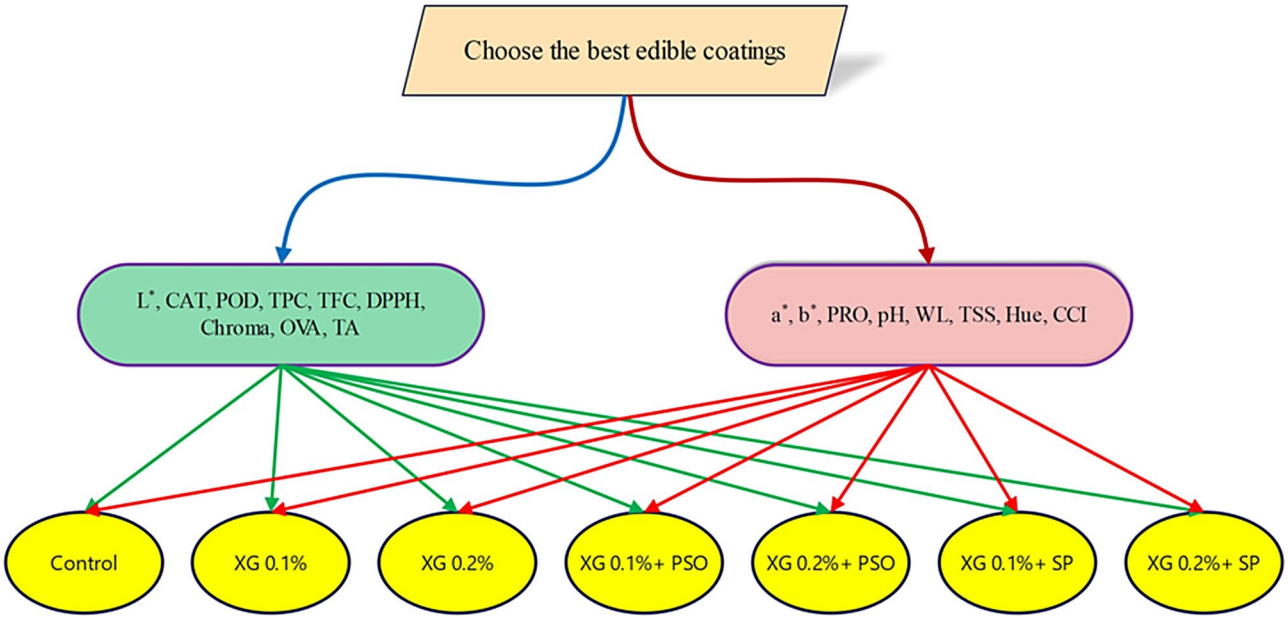

Fig. 1 Hierarchical tree for optimal edible coating selection

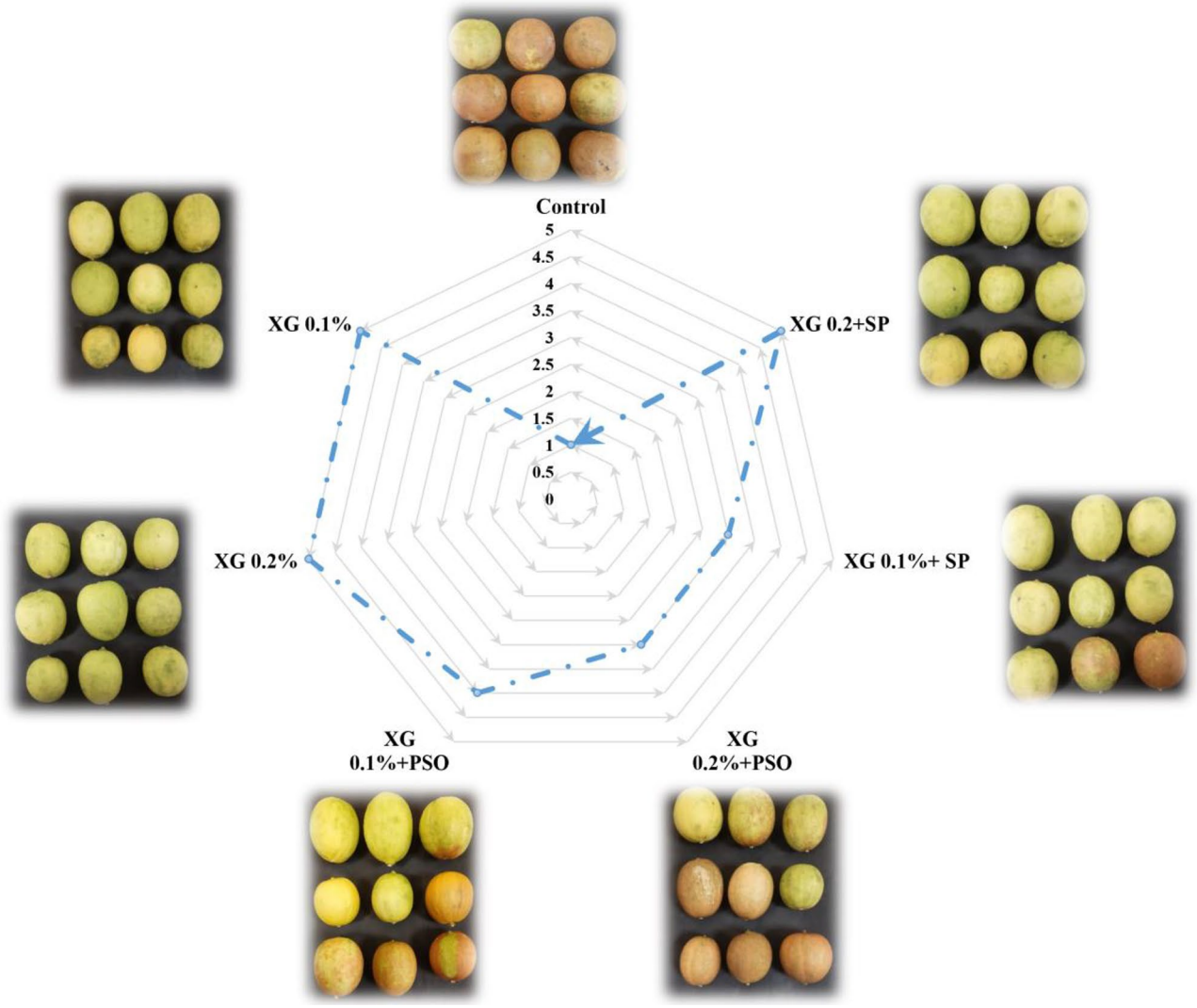

Fig. 2 The impact of treatments (Control, XG 0.1%: Xanthan 0.1%, XG 0.2%: Xanthan 0.2%, XG 0.1%+PSO: Xanthan 0.1% + Pomegranate Seed Oil, XG 0.2%+PSO: Xanthan 0.2% + Pomegranate Seed Oil, XG 0.1%+SP: Xanthan 0.1% + *Spirulina Platensis*, XG 0.2%+SP: Xanthan 0.2% + *Spirulina Platensis*) on the Overall Visual Acceptability of Mexican lime fruit stored for 24 days at 20 ± 2 ℃ and 50–60% RH. The data represent the mean values of $n = 3$, and the error bars indicate standard errors (SE) of the means. Statistical analysis was performed using the LSD test at the $P \leq 0.05$ level

SP (363 U/mgFW) treatments, followed by the XG 0.1% treatment (Fig. 5c).

Color parameters

As observed in Fig. 6, in most treatments, the L* value gradually increased during storage. However, the XG 0.1% + SP treatment showed an initial increase followed by a decreasing trend. At the end of the experiment, analysis revealed that there was no significant deviation in the outcomes between the control group and those subjected to the various treatments (Fig. 6a).

Significant changes in a* values were observed in the treated samples compared to the control. During storage, treatments displayed a lower a* value (greater greenness) compared to the control. Specifically, different concentrations of XG and their combination with *Spirulina* demonstrated noticeable greenness compared to the control, preventing the color change of the fruit peel (Fig. 6b).

Except for the XG 0.1% + SP and XG 0.2% + PSO treatments, which initially exhibited a decrease and then showed an increasing trend, the other treatments gradually increased during storage. Specifically, the XG treatments at 1% and 2% concentration showed a significant increase compared to the control at the end of the experiment. However, no significant difference was observed when comparing the control with the other treatments (Fig. 6c).

During the storage period, the chroma index, a measure of fruit color intensity, exhibited a rising trend,

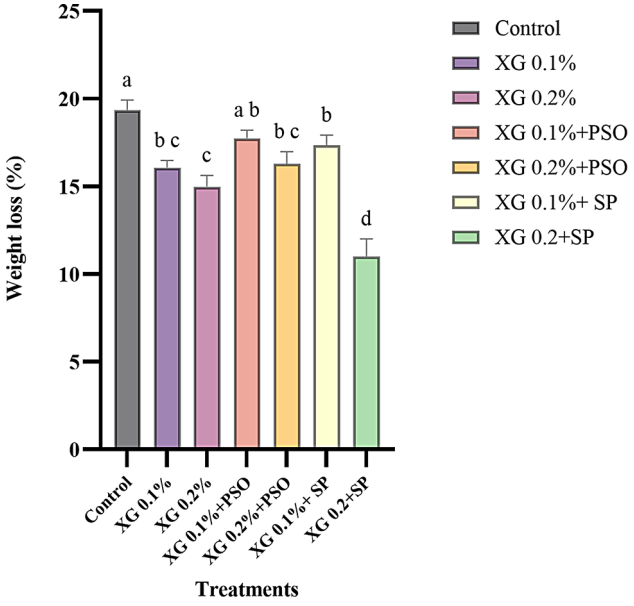

Fig. 3 The impact of treatments (Control, XG 0.1%: Xanthan 0.1%, XG 0.2%: Xanthan 0.2%, XG 0.1%+PSO: Xanthan 0.1% + pomegranate seed oil, XG 0.2%+PSO: Xanthan 0.2% + pomegranate seed oil, XG 0.1%+SP: Xanthan 0.1% + *Spirulina Platensis*, XG 0.2%+SP: Xanthan 0.2% + *Spirulina Platensis*, PSO: pomegranate seed oil (0.05%)) on the weight loss of Mexican lime fruit stored for 24 days at 20 ± 2 ℃ and 50–60% RH. The data represent mean values of $n = 3$, and the error bars indicate standard errors (SE) of the means. Statistical analysis was performed using the LSD test at the $P \leq 0.05$ level

reaching its peak particularly in the treatments involving XG 0.1%, XG 0.2%, and XG 0.1%+ SP. Conversely, the lowest chroma index value was observed in the treatment with PSO by the end of the storage period, as illustrated in Fig. 6d.

The Hue index exhibited a significant decrease on the 12th day and remained relatively stable until the 24th day across all treatments. Amongst the treatments, the XG 0.2%+ SP treatment displayed the lowest Hue compared to the other treatments (Fig. 6e).

Total soluble solids (TSS), pH and TA

As illustrated in Fig. 7, there is a discernible gradual increment in the total soluble solids (TSS) content of the fruit over the storage period. However, this increase manifests at a notably subdued rate within the treated groups when compared against the control group, indicating a moderated alteration in TSS levels attributable to the applied treatments. Consequently, all treatments exhibited a lower TSS level compared to the control. The maximum (7.9%) and minimum (6.9%) TSS content were observed in the control and XG 0.2%, respectively (Fig. 7a).

As illustrated in Fig. 7, the titratable acidity (TA) of the samples decreased during storage. However, some treatments exhibited fewer reductions compared to the control. Specifically, the treatments with two concentrations of XG and their combination with *Spirulina* demonstrated a significantly higher level of TA compared to the control. These treatments displayed a significant advantage over the control in terms of acidity preservation (Fig. 7b).

In Fig. 7c, it is evident that pH changes during storage in treatments, other than XG 0.2%, were minimal, showing a slight increase compared to the initial day.

TOPSIS analysis

The study used the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate different treatments for lemon storage, taking multiple criteria into account. Results varied across different indicators. The XG 0.2%+PSO treatments excelled in the L* index, whereas the XG 0.2%+SP and control treatments showed the lowest performance. For the a* index, XG 0.2%+SP was the best, with the control being the least desirable. In enzyme activity (CAT, PPO, POD), control had poor results, while XG 0.2%+SP and XG 0.2% treatments were preferred. The control was least favorable for total phenol and flavonoid content, with XG 0.2%+SP being the most beneficial. XG 0.1%+SP was optimal for antioxidant activity. The control performed worst in weight loss index and TSS content, with XG 0.2%+SP and XG 0.2% being the best. For hue and Chroma index, XG 0.2%+SP and XG 0.2% were the optimal treatments, respectively. Marketability analysis favored XG 0.1%, and for titratable acid index, the control and XG 0.2% treatments were the least and most effective, respectively. Overall, XG 0.1% treatment was identified as the optimal choice across all evaluated criteria (Fig. 8).

Correlation and principal component analysis (PCA)

The Hierarchical Cluster Analysis (HCA) classified the parameters and treatments into distinct groups and clusters. Group I included parameters like POD, antioxidant activity, PPO, and Hue, while Group II contained all other parameters. Treatments were divided into two clusters: Cluster IV with the control and PSO 0 treatments, and Cluster V comprising the rest of the treatments. A significant negative correlation was noted between the control and PSO 0 treatments and the Hue parameter, whereas a strong positive correlation was found between XG 0.1%, XG 0.2%, and XG 0.2% + SP treatments and CAT activity (Fig. 9a).

The Principal Component Analysis (PCA) further investigated the relationships between parameters and treatments. The PCA biplot highlighted two main groups, with F1 accounting for 55.03% of the variance and F2 covering 25.20%. F1 showed positive loadings for weight loss (%), TSS, and L*, but negative loadings for TA, total flavonoid, and antioxidant activity. F2 had positive loadings

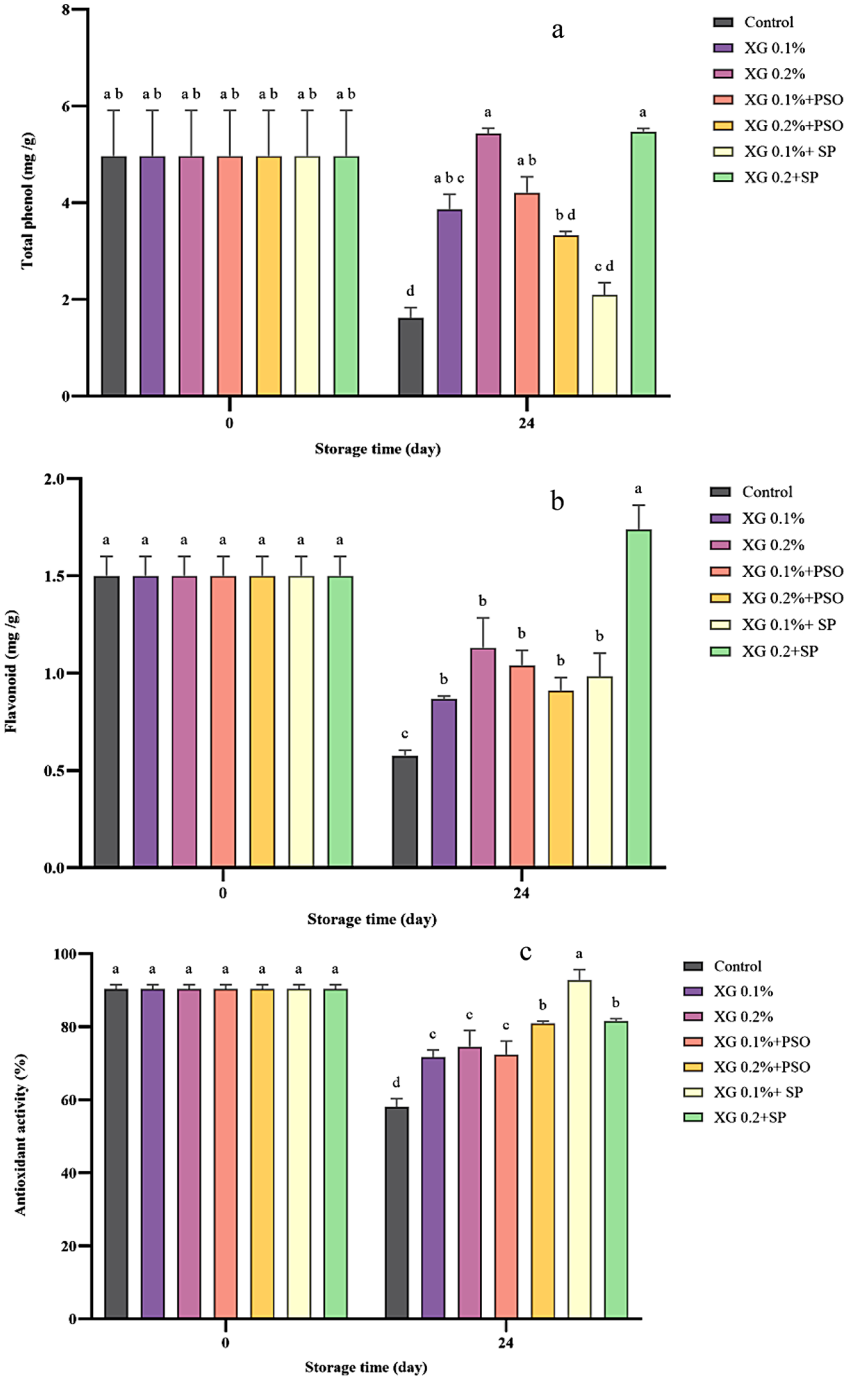

Fig. 4 The impact of treatments (Control, XG 0.1%: Xanthan 0.1%, XG 0.2%: Xanthan 0.2%, XG 0.1%+PSO: Xanthan 0.1% with Pomegranate Seed Oil, XG 0.2%+PSO: Xanthan 0.2% + Pomegranate Seed Oil, XG 0.1%+SP: Xanthan 0.1% + *Spirulina Platensis*, XG 0.2%+SP: Xanthan 0.2% + *Spirulina Platensis*) on (**a**) Total phenols, (**b**) Flavonoids, and (**c**) Antioxidant of Mexican lime fruit stored for 24 days at 20 ± 2 ℃ and 50–60% RH. The data represent mean values of $n = 3$, and the error bars indicate standard errors (SE) of the means. Statistical analysis was performed using the LSD test at the $P \leq 0.05$ level

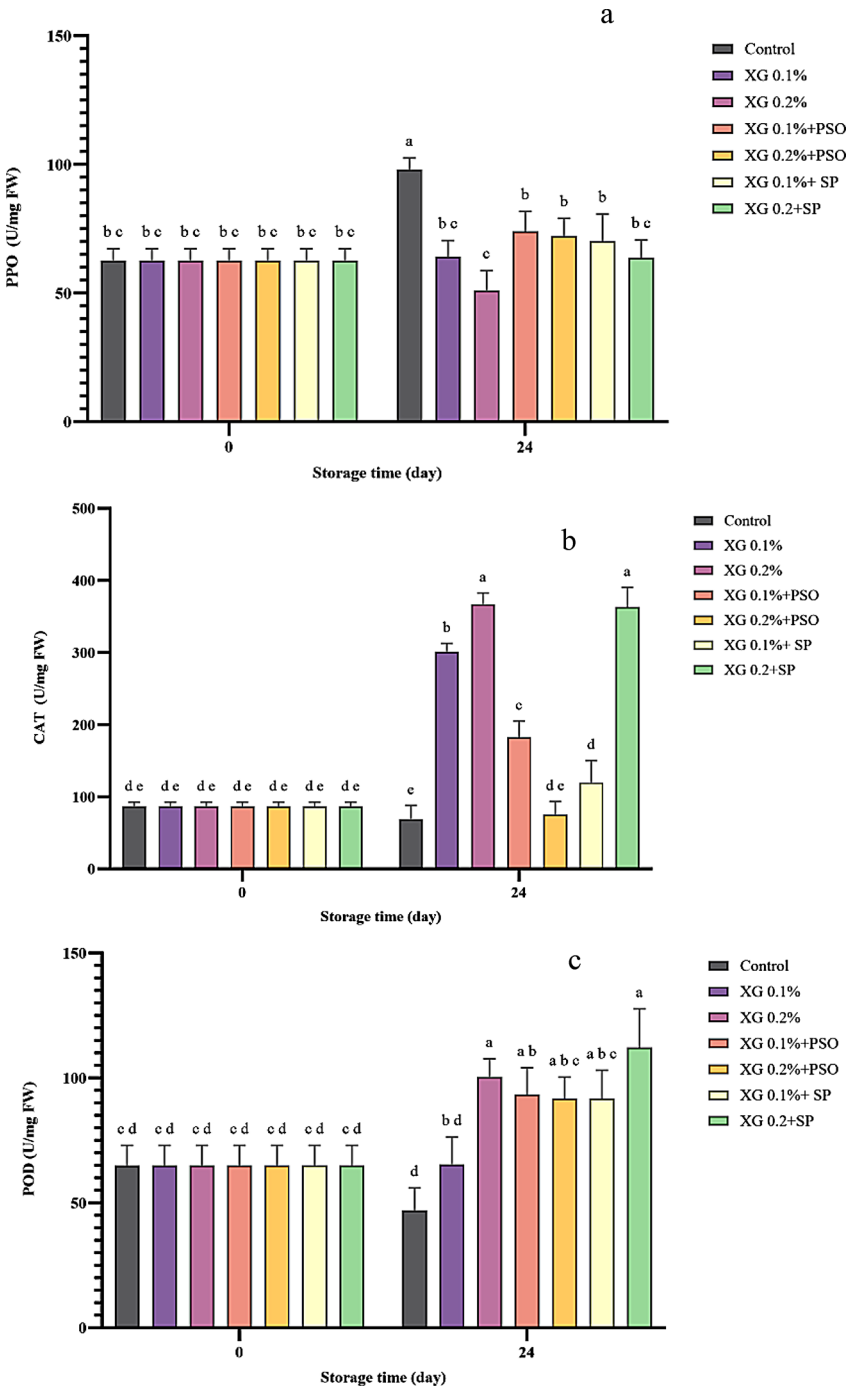

Fig. 5 The impact of treatments (Control, XG 0.1%: Xanthan 0.1%, XG 0.2%: Xanthan 0.2%, XG 0.1%+PSO: Xanthan 0.1% with Pomegranate Seed Oil, XG 0.2%+PSO: Xanthan 0.2% + Pomegranate Seed Oil, XG 0.1%+SP: Xanthan 0.1% with *Spirulina Platensis*, XG 0.2%+SP: Xanthan 0.2% + *Spirulina Platensis*) on (**a**) Polyphenol oxidase, (**b**) Catalase, and (**c**) Peroxidase of Mexican lime fruit stored for 24 days at 20 ± 2 ℃ and 50–60% RH. The data represent mean values of $n = 3$, and the error bars indicate standard errors (SE) of the means. Statistical analysis was performed using the LSD test at the $P \leq 0.05$ level

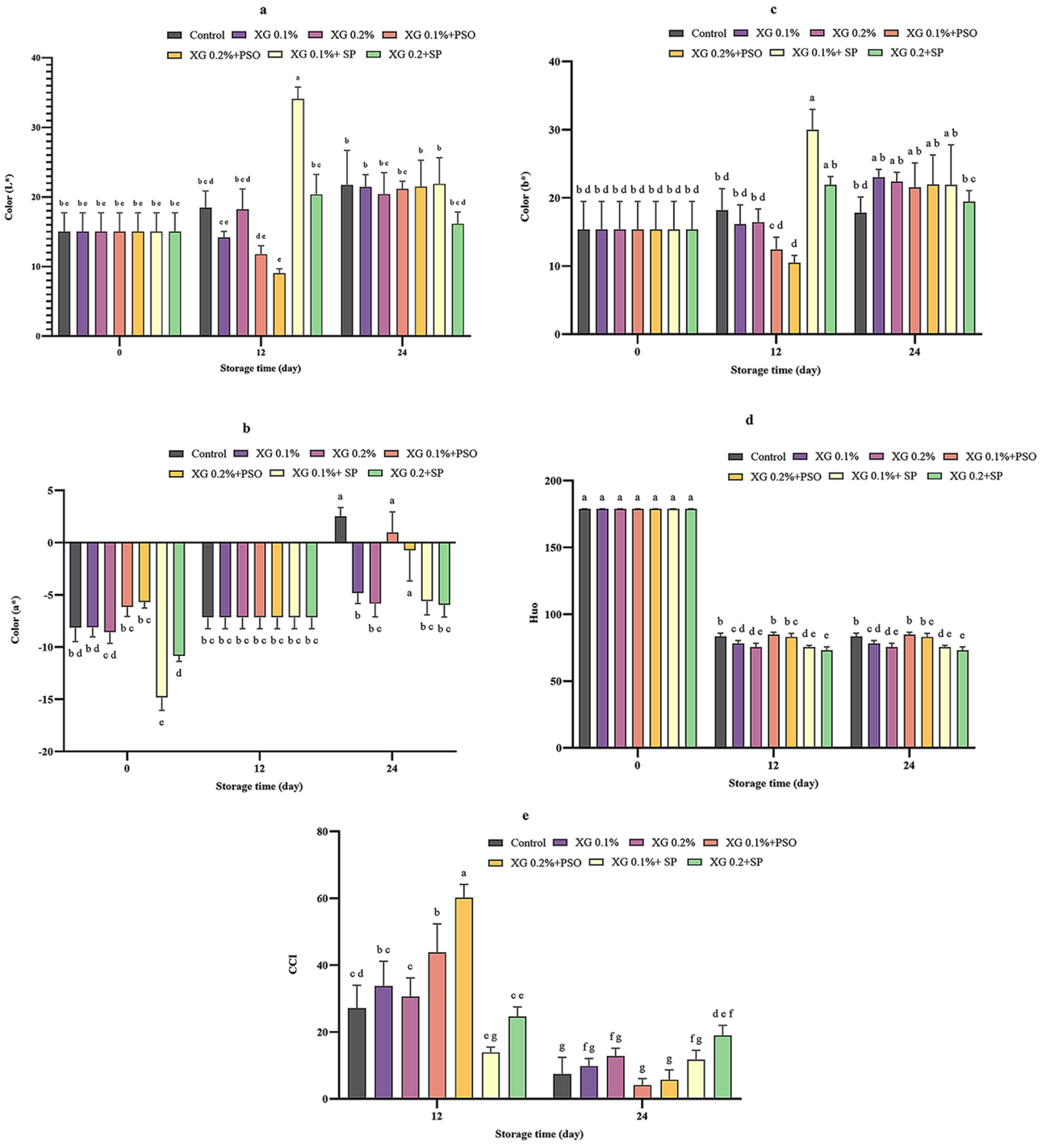

Fig. 6 The impact of treatments (Control, XG 0.1%: Xanthan 0.1%, XG 0.2%: Xanthan 0.2%, XG 0.1%+PSO: Xanthan 0.1% + pomegranate seed oil, XG 0.2%+PSO: Xanthan 0.2% + pomegranate seed oil, XG 0.1%+SP: Xanthan 0.1% + *Spirulina Platensis*, XG 0.2%+SP: Xanthan 0.2% with *Spirulina Platensis*) on (**a**) L*, (**b**) a*, (**c**) b*, (**d**) Hue, and (**e**) CCI of Mexican lime fruit stored for 24 days at 20 ± 2 ℃ and 50–60% RH. The data represent mean values of $n = 3$, and the error bars indicate standard errors (SE) of the means. Statistical analysis was performed using the LSD test at the $P \leq 0.05$ level

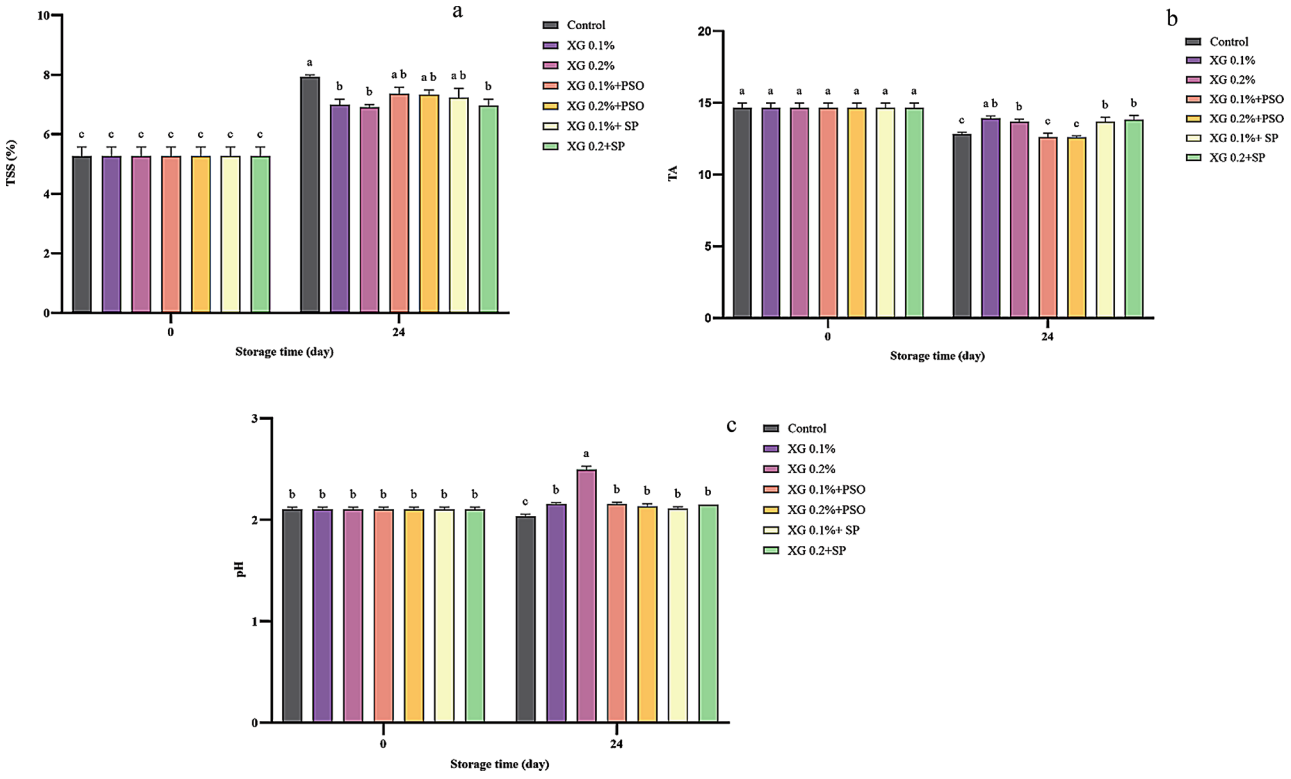

Fig. 7 The impact of treatments (Control, XG 0.1%: Xanthan 0.1%, XG 0.2%: Xanthan 0.2%, XG 0.1%+PSO: Xanthan 0.1% with Pomegranate Seed Oil, XG 0.2%+PSO: Xanthan 0.2% with Pomegranate Seed Oil, XG 0.1%+SP: Xanthan 0.1% with *Spirulina Platensis*, XG 0.2%+SP: Xanthan 0.2% with *Spirulina Platensis*) on (**a**) Total Soluble Solids (TSS), (**b**) pH, and (**c**) Titratable acidity (TA) of Mexican lime fruit stored for 24 days at 20 ± 2 ℃ and 50–60% RH. The data represent mean values of $n = 3$, and the error bars indicate standard errors (SE) of the means. Statistical analysis was performed using the LSD test at the $P \leq 0.05$ level

Treatment	L*	a*	b*	CAT	PPO	POD	pH	TPC	TFC	DPPH	WL	TSS	Hue	Chroma	CCI	OVA	TA	TOPSIS
Control	6	7	1	7	7	7	1	7	7	6	7	7	6	6	3	7	7	7
XG 0.1%	4	4	7	3	3	6	4	4	6	7	3	3	4	1	4	1	2	2
XG 0.2%	5	2	6	1	1	2	7	2	2	4	2	1	2	2	6	2	1	1
XG 0.1%+PSO	1	6	3	4	6	3	5	3	3	5	6	6	7	5	1	4	6	5
XG 0.2%+PSO	2	5	5	6	5	5	6	6	5	2	4	5	5	4	2	5	5	6
XG 0.1%+ SP	3	3	4	5	4	4	2	5	4	1	5	4	3	3	5	6	4	4
XG 0.2+SP	7	1	2	2	2	1	3	1	1	3	1	2	1	7	7	3	3	3

Fig. 8 Treatment prioritization in the comprehensive assessment of lime quality using TOPSIS across multiple criteria. The numbers displayed indicate the priority of each treatment selection for individual criteria, while the last column represents the overall treatment selection based on all features

for CAT, POD, and PH, but negative ones for PPO and a*. The analysis pointed out that PPO was closely associated with the PSO 24 treatment. Additionally, the PSO 24 treatment displayed unique effects in relation to F1 compared to the control treatment, while the XG 0.2%24 and XG 0.2%+SP24 treatments showed differences from both PSO 24 and control treatments in terms of F2 (Fig. 9b).

Discussion

The results of this study demonstrated that treating lime fruits with XG 0.1%, XG 0.2%, and XG 0.2% + SP resulted in significantly higher acceptance compared to the control group. These treatments effectively maintained fruit color and freshness, showing no signs of dehydration, peel shriveling, or discoloration. In contrast, other treatments exhibited significant signs of browning and peel dryness, leading to a substantial decrease in fruit market acceptance. Edible coatings have been shown to effectively extend the shelf life of produce by preserving its quality and sensory characteristics [34]. Xanthan gum coating enhances visual acceptability by forming a smooth barrier, reducing moisture loss, maintaining color and texture, and being transparent, preserving fruit appearance effectively. In addition, the transparency of xanthan gum does not alter the natural appearance of the fruit, contributing to its high visual acceptability [9]. Studies have shown that treating pomegranate fruits with 2% chitosan significantly preserves visual quality

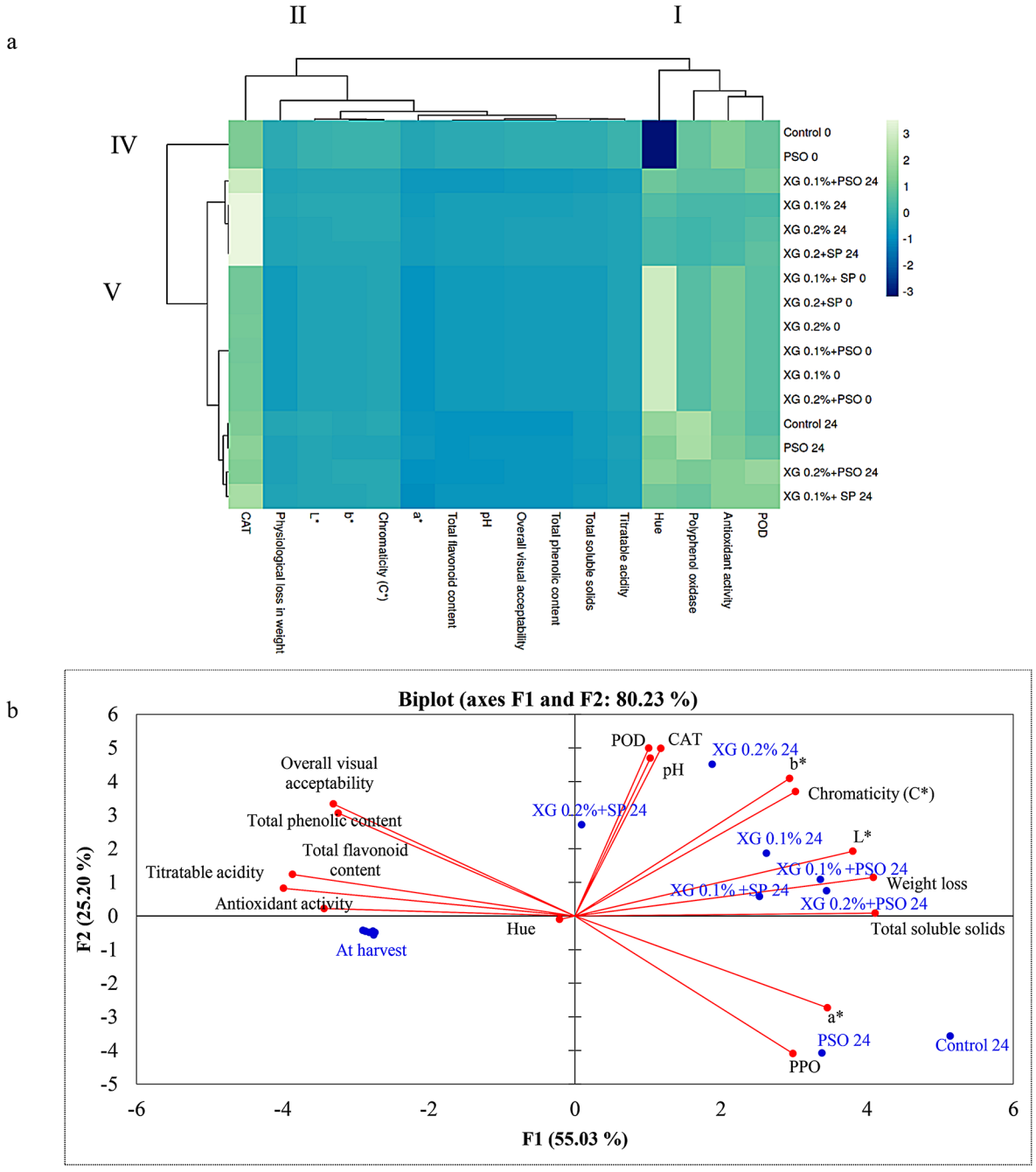

Fig. 9 (**a**) Hierarchical clustering analysis (HCA) of the edible coating treatments and variable trait relationships in Mexican lime fruit, including a heatmap of Pearson correlation coefficients (r values) for variable traits. The colored scale shows the r coefficient values (*r* = -3 to 3) indicating positive (green) and negative (blue) correlations, respectively. (**b**) Principal component analysis (PCA) of treatments and variable trait relationships in Mexican lime fruit, including PCA loading plots of the examined variable traits

during cold storage by maintaining the rind color, reducing browning, and imparting a thin, glossy layer to the fruit's surface [35]. In line with our findings, it has been shown that the guava fruits coated with 0.75% xanthan gum achieved the highest scores for overall acceptability on the 15th day of storage, with fruits coated with 0.50% xanthan gum also performing well [9].

Weight loss during storage occurs due to evapotranspiration, which is accelerated by elevated metabolic processes [36].To mitigate this issue, postharvest interventions, including the application of specialized coatings, have been investigated to alter fruit physiology and minimize respiration and moisture loss. The observed decrease in weight loss in coated fruits can be attributed

to the development of a protective film on the fruit surface, which functions as a semipermeable barrier to water transfer, However, it is well-established that the application of coatings effectively restricts water loss, thereby preserving fruit weight throughout the storage period [37]. The XG 2% + SP treatment significantly reduced weight loss in fruits by limiting transpiration, thereby helping to maintain quality and juice content during postharvest storage [38]. Xanthan gum and lemongrass essential oil coatings on kinnow mandarin fruits significantly reduce weight loss, especially evident on the 30th day of storage [39]. This is supported by the findings of [40], who also observed weight retention in papaya fruit treated with xanthan gum. The results of this study demonstrate that increasing the concentration of xanthan gum effectively reduced weight loss in mango fruit compared to the control group. Similarly [41] and [42], reported reductions in postharvest weight loss in mango and rambutan under various storage conditions by using gum Arabic and xanthan gum, respectively, through the control of water loss and respiration rate.

The assessment of total phenol content serves as a vital criterion for evaluating the antioxidant capacity of a sample. Phenolic compounds, synthesized as secondary metabolites during maturation and fruit ripening, contribute not only to the nutritional quality of fruits but also influence fruit color, a crucial parameter for fruit juice processing [43, 44]. Indeed, coatings significantly influence the metabolism of phenolic compounds by establishing a controlled microenvironment around the fruit. This altered environment serves as a protective barrier, effectively reducing the rates of respiration and oxidation of phenolic compounds. A primary mechanism underlying this protective effect is the inhibition of PPO activity, the enzyme responsible for catalyzing the oxidation of phenolic compounds [45]. The decline in phenolic content observed in control fruits at the conclusion of storage aligns with the natural decrease in phenolic content during senescence [46]. The XG 2%+ SP treatment resulted in the highest levels of phenol and flavonoid contents may by modifying the fruit ripening process through the reduction of gas exchange, water loss, and oxidation, as well as altering the internal gas composition and ethylene production [47]. The application of xanthan gum coatings on fruits, such as limes and mangoes, has been shown to effectively preserve phenolic content, supporting the idea that modifying ripening processes can increase the synthesis and accumulation of phenolic compounds [48]. The findings reported by [49] are in close agreement with our own results, as they also noted a reduction in the total antioxidant activity of strawberries during storage. However, their research demonstrated that applying edible coatings to the fruits effectively preserved higher levels of total antioxidant activity. This protective effect is attributed to the formation of a thin coating film on the fruit surface, which creates a controlled microenvironment that restricts oxygen availability, thereby limiting the enzymatic oxidation of phenolic compounds [50]. Xanthan gum coatings have been found to protect phenolic compounds in guava fruits during storage, preserving their antioxidant properties and reducing oxidative damage [9]. Research has demonstrated that coating Jamun fruit (Indian blackberry) with xanthan gum and a bio surfactant significantly increased phenolic compounds, thereby enhancing its antioxidant properties during storage [51].

Following fruit harvesting and during cell senescence, oxidative stress occurs, leading to the generation of reactive oxygen species (ROS) capable of causing oxidative damage to fruit tissues [52]. Numerous studies have demonstrated the beneficial impact of edible coatings on maintaining the activity of antioxidant enzymes in fruits during storage. Coatings such as gum Arabic and xanthan establish a protective layer around the fruit, thereby reducing exposure to external factors that may contribute to enzyme degradation [47]. Edible coatings effectively preserve antioxidative enzyme activity in fruits, acting as a protective barrier against ROS and significantly improving their postharvest storage potential [53]. Research [54] highlights the profound influence of edible coatings on the functionality of antioxidant enzymes in fruits. Their investigation concentrated on enzymes including catalase, peroxidase, superoxide dismutase, and ascorbate peroxidase, which are integral in mitigating oxidative stress and maintaining the nutritional integrity of fruits. Xanthan gum edible coatings have emerged as a promising method for improving postharvest fruit quality by modulating enzymatic activities, such as CAT and POD, which play a pivotal role in oxidative stress reduction. Studies have shown that xanthan gum coatings significantly enhance CAT and POD activities. For example, guava fruits treated with 0.75% xanthan gum displayed the highest CAT activity, leading to diminished oxidative damage and extended shelf life [9]. Similarly, Kinnow mandarins coated with xanthan gum and lemongrass oil exhibited improved CAT and POD activities, resulting in better retention of titratable acidity and overall fruit quality during storage [35]. Additionally [55], reported that *Spirulina* is rich in antioxidants including CAT, vitamins, reduced glutathione, total phenols, flavonoids, tannins, carbohydrates, and proteins, which may boost the antioxidant defense system by increasing CAT and POD activity. This supports the idea that plants can enhance POD activity under stress or oxidative conditions as a defense mechanism against ROS-induced damage [56]. Edible coatings, particularly XG 0.2% and XG 0.2% + SP treatments, have proven effective in slowing fruit browning during storage by forming a barrier that reduces

water loss and gas exchange, thereby lowering respiration rates and inhibiting browning enzymes like POD and PPO, ultimately preserving fruit color by controlling internal conditions and reducing enzymatic and oxidative browning. The study on mango fruits has demonstrated that xanthan gum edible coating combined with pomegranate peel extract effectively reduces PPO enzyme activity during storage [57]. Similarly, it has been shown that a xanthan gum coating enriched with cinnamic acid effectively inhibits PPO enzyme activity, thereby delaying browning in fresh-cut pears and extending their shelf life up to 8 days during storage [58].

Color stands out as a pivotal quality attribute in fruits, serving a significant role in indicating maturity and ripening. In the context of fresh-market limes, peel color emerges as a primary determinant of fruit quality, with fruits classified into distinct classes based on the green color of the peel at harvest [59]. Coatings effectively reduce chlorophyll loss and delay ripening by creating a barrier that elevates CO_2 levels, reduces O_2, and limits ethylene biosynthesis, thus slowing color changes in fruit [60]. Non-coated limes exhibited higher a* values, indicating a more pronounced red/green color, gradually decreasing over the storage period. In contrast, coated limes retained their color more effectively [61]. Improved color retention in fruits coated with xanthan gum and PSO is due to the modified atmosphere they create, which helps minimize color variations during storage, regardless of the storage time [62]. Similar results were reported by [63] that application coatings on fruits can slow the transition from green to yellow or red by reducing chlorophyll degradation and delaying carotenoid synthesis, thus preserving the green color for a longer period. Coating limes not only preserved their color by maintaining chlorophyll levels and slowing carotenoid synthesis, leading to less yellowing and brighter fruits during storage, but also created a modified atmosphere that reduced color disparities [64]. Fruit coated with xanthan 0.1%+ PSO and xanthan 0.2%+ PSO, experienced delayed metabolism. Coating fruits with xanthan gum and *Spirulina platensis* may preserve color and extend shelf life by delaying pigment changes.

The increase in TSS during storage is due to water loss, breakdown of polysaccharides, pectin, and starch, changes in juice content, and degradation of organic compounds into mono- and disaccharides [65]. The reduced rate of TSS increase in coated fruits is attributed to the coatings' ability to decrease respiration and physiological ripening activities [66]. Respiration causes the consumption and conversion of organic acids into simple sugars, resulting in a decrease in TA and an increase in TSS and pH [67]. Edible coatings on fruits can increase carbon dioxide levels, thus reducing organic acid loss by lowering respiration and ethylene production [68]. Changes in acidity can occur due to the transformation of acids into sugars and their subsequent utilization in metabolic processes during the maturation of fruits. The results of our experiment align with the findings of [40], who observed a shift in pH and acidity in papaya fruits due to xanthan coating. The findings align well with the earlier research by [69, 70] observed that applying edible coatings to litchi and mango fruits effectively maintains TSS by mitigating the hydrolytic conversion of sugars and juice leakage, likely due to the coatings' properties in reducing oxidation, respiration rate, and moisture loss. Our research corroborates the hypothesis that edible coatings can positively impact the physicochemical properties of fruits throughout storage, aiding in the preservation of critical parameters such as TSS and TA. These coatings achieve this by modulating the diffusion of substances and minimizing moisture loss, thereby extending the fruit's freshness and structural integrity over an extended period.

Conclusion

This study demonstrated that xanthan gum-based edible coatings, either alone or enriched with *Spirulina platensis* extract, significantly improved the quality and shelf life of Mexican lime fruits stored at 20±2 °C and 50–60% relative humidity. Treated fruits exhibited lower TSS, higher TA, improved greenness (negative a* values), increased activity of antioxidant enzymes (CAT and POD), and decreased PPO activity. Among the treatments, the combination of 0.2% xanthan gum and 1% *Spirulina platensis* extract was most effective in minimizing weight loss and preserving phenolic compounds. These findings highlight the potential of xanthan gum-based coatings, enriched with *Spirulina platensis*, as a promising and environmentally friendly solution for extending the shelf life and maintaining the quality of Mexican lime fruits. This approach offers a valuable strategy for postharvest management of citrus fruits.

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Author contributions
Mahbobeh Mohammadi: Do experiment, Formal analysis, Investigation, Writing – original draft. Somayeh Rastegar: Funding acquisition, Resources, Project administration, Review & editing, Resources, Investigation. Abbas Rohani: Analysis, Review & editing. All authors have read and agreed to the published version of the manuscript.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The plant material lime fruit was purchased from a commercial orchard in Rodan city in Hormozgan province. This article did not contain any studies with human participants or animals and did not involve any endangered or protected species. The experimental research on plants is comply with relevant institutional, national, and international guidelines and legislation.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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