Engineering Properties of Tomato Affected by Ultrasonic and Packaging During Storage

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Abstract

In this study, ultrasonic radiation (US), packaging film, controlled atmosphere packaging, and controlled storage temperature were utilized for tomaoto packaging. Prior to packaging, the samples underwent ultrasonic treatment and were subsequently packed using polyethylene film (PE) and polyethylene film equipped with 2% nanoclay particles (Nano film) under both normal atmospheric conditions and modified atmosphere (MA) (5% O_2 + 3% CO_2). These tomatoes were stored at 25°C and 4°C for 28 days. Weekly assessments of storage properties included an examination of physical aspects such as moisture and color indices, chemical factors like pH, total soluble solids (TSS), lycopene, and total phenolic content, as well as mechanical properties encompassing penetration force and elastic modulus. The results indicated that the storage had a detrimental effect on the trends of property changes. Utilizing a modified atmosphere, appropriate storage temperatures, and applying ultrasonic treatment and Nanofilm were found to regulate specific properties effectively. Statistical analysis revealed a significant impact of the applied treatments on most properties at both the 1% and 5% significance levels. On the other hand, an Artificial Neural Network (ANN) was employed for data prediction, and the results showed that the best structure in predicting the physical, mechanical, and chemical properties was 5-10-11. O_2 and CO_2 were predicted with high accuracy with R^2 = 0.93 and R^2 = 0.86, respectively, which has shown the accurate performance of the ANN in predicting the data with the selected structure.

Keywords: Packaging, Storage, Tomato, Ultrasonic

Introduction

In today's context, characterized by shifts in dietary preferences and increased consumption of fatty foods, the significance of fruits and vegetables in delivering essential nutrients and promoting health and food security has become paramount. Among these, tomatoes (*Solanum lycopersicum* L.) are one of the most widely consumed products globally, available in fresh and processed forms (D'Aquino *et al.*, 2016; Olveira-Bouzas, Pita-Calvo, Lourdes Vázquez-Odériz, & Ángeles Romero-Rodríguez, 2021). According to the FAO's 2021 reports, approximately 6 million hectares of land worldwide are dedicated to tomato cultivation, resulting in an annual production of nearly 256 million metric tons. In Iran, 77,492 hectares of agricultural land are designated for tomato cultivation, yielding over 3 million metric tons of produce (Anonymous, 2021). Tomatoes, with their high moisture content of approximately 90%, require specific storage and preservation conditions due to the substantial impact of moisture content on agricultural products' perishability and shelf life. From a nutritional perspective, tomatoes contain beneficial antioxidant compounds, including β-carotene, lycopene, ascorbic acid, and phenolic compounds (Walubengo, Orina, Kubo, & Owino, 2022). Like other agricultural products, tomatoes continue to undergo respiration even after harvesting, progressing through stages of growth and aging. This post-harvest trajectory alters physical, structural, and chemical properties. These changes typically result in a decline in quality, characterized by weight loss, shifts in color indicators, modifications in chemical attributes, and variations in texture and mechanical parameters, ultimately accelerating product deterioration and waste generation (Osae *et al.*, 2022). The escalation of spoilage and waste during post-harvest stages directly impacts the livelihoods of farmers and sellers and the food security of communities. Hence, identifying effective treatments for preserving various agricultural products, including tomatoes, during storage is essential. In recent years, various methods have been employed to extend the shelf life and maintain the quality of agricultural products during storage. These methods encompass nanofilms, Modified Atmosphere Packaging (MAP), and edible and non-edible coatings (Gholami, Aghili nategh, & Rabbani, 2023). Emerging techniques such as ultrasonic waves, high-voltage pulse electric fields, and other physical methods have also found their place in real-world applications (Osae *et al.*, 2022; Zhao *et al.*, 2023). The utilization of modern industrial packaging methods for food and agricultural products remains somewhat limited in developing nations. Consequently, substantial scientific research in this field can potentially drive the industrialization and broader adoption of these practices in agriculture and the food industry. Recently, numerous studies have explored innovative packaging methods to preserve the quality and extend the shelf life of agricultural products. These investigations have encompassed the evaluation of these methods' impact on various properties of agricultural products, including the physical, mechanical, chemical, sensory, and microbial aspects. Notable research on the evaluation of the shelf life of agricultural products under different packaging conditions has been conducted in recent years. An investigation into the impact of modified atmosphere packaging on the shelf life of tomatoes was done by Olveira-Bouzas *et al.* in 2021. A modified atmosphere packaging (MAP) system in pallets was developed, and its effect on physico-chemical and sensory characteristics and shelf-life of tomato was evaluated. Their results showed that MAP delayed color evolution and reduced the firmness loss, biosynthesis of lycopene, and decay rate of tomatos. A separate study conducted by Gholami, Ahmadi, and Ahmadi in 2020 examined the shelf life of white mushrooms. Their research showed that the use of nano-film and modified atmosphere has had a positive effect on preserve the quality of mushrooms during storage. Zhao *et al.* (2023) conducted a study examining the post-harvest traits of tomatoes exposed to high-voltage electrostatic fields (HVEF). Their results showed that compared to the control group, the weight loss and the color change of cherry tomatoes treated by HVEF decreased by 8.48%–23.00%, and 25.08%–58.57%, respectively. HVEF treatment resulted in higher hardness and Vitamin C content, stronger antioxidant capacity, lower microbial loads and microstructure damage. Uba, Esandoh, Zogho, and Anokye (2020) have carried out an exploration of the physical and mechanical attributes of local tomatoes in Ghana. In 2022, Osae *et al.* performed an analysis of how coatings such as beeswax influence the chemical properties of tomatoes. They used some edible coating as new methods for pereserving the quality of tomato during storage (Gholami *et al.*, 2020; Olveira-Bouzas *et al.*, 2021; Osae *et al.*, 2022; Sridhar, Makroo, & Srivastava, 2022; Uba *et al.*, 2020; Zhao *et al.*, 2023).

Given the extensive research on various tomato varieties, the present study focuses on evaluating the effects of specific packaging conditions on tomatoes' physical, mechanical, and chemical properties during the storage period. While numerous studies have addressed tomatoes during post-harvest stages, none have specifically examined the combination of Modified Atmosphere Packaging (*MAP*), Nanofilm utilization, and Ultrasonic treatment. This research entailed the controlled introduction of gases at defined proportions (5% O_2 + 3% CO_2), the application of polyethylene film enhanced with nano-sized particles, and the implementation of ultrasonic treatment. The properties of the tomatos were consistently evaluated throughout the storage period.

Materials and Methods

Sample preparation

Fresh tomatoes were sourced from local greenhouses in Hamedan Province (34.7983° N, 48.5148° E), Iran. To ensure uniformity in ripeness, color, and size and to minimize errors, all tomatoes were manually selected at the fully ripe stage. Following harvest, the tomatoes were transported to the laboratory and stored under identical conditions (4°C temperature and 60-70% relative humidity) until the commencement of the experiments and packaging.

Treatments and packaging

The samples were divided into two groups, with one group subjected to ultrasonic conditions. An ultrasonic device, manufactured in Iran (Panasonic 7500s), was utilized to apply the ultrasonic treatment. This setup allowed for individual placement of the samples inside the device and exposure to radiation for 25 minutes with a frequency of 28 kHz. Samples, both exposed to radiation and those left unexposed, were packaged using regular polyethylene (PE) and polyethylene film equipped with 2% nanoclay (Nano film) particles. PE and Nano films were obtained from the Iranian Polymer Research Institute. The packaging process involved modified atmosphere packaging, while another group was sealed with a standard atmospheric condition. Packaging and gas injection was carried out using a semi-automatic Tray-Sealer packaging machine (STS007, West Asia Steel Co). After applying ultrasonic radiation, gas injection, and using regular and nanofilms, all samples were again categorized into two groups. The first group was stored at a temperature of 25°C, while the second group was placed in a refrigerator at 4°C for 28 days. To ensure accurate sample identification, each package was assigned a unique code (Table 1). Throughout the storage period, samples from each treatment group were examined every 7 days. It is essential to note that all tests were conducted in triplicate.

Table 1- Codes for treatment packages

Code	Ultrasound	Temperature	Film	Atmosphere	Code	Ultrasound	Temperature	Film	Atmosphere
1111	Unexposed	25°C	PE	Ambient	2111	Exposed	25°C	PE	Ambient
1112	Unexposed	25°C	PE	MAP	2112	Exposed	25°C	PE	MAP
1121	Unexposed	25°C	NANO	Ambient	2121	Exposed	25°C	NANO	Ambient
1122	Unexposed	25°C	NANO	MAP	2122	Exposed	25°C	NANO	MAP
1211	Unexposed	4°C	PE	Ambient	2211	Exposed	4°C	PE	Ambient
1212	Unexposed	4°C	PE	MAP	2212	Exposed	4°C	PE	MAP
1221	Unexposed	4°C	NANO	Ambient	2221	Exposed	4°C	NANO	Ambient
1222	Unexposed	4°C	NANO	MAP	2222	Exposed	4°C	NANO	MAP

Gas composition

In this research, packages with dimensions of 20 cm × 15 cm were selected and divided into two groups. The first group was filled with normal atmosphere (air) and the second group was filled with modified atmosphere (5% O_2 + 3% CO_2 + 92% N_2). During the storage period, gas changes inside the packages were evaluated weekly using a gas meter (Oxybaby 6i, WTT-GASTECHNIK).

Physical properties

The moisture percentage is one of the primary factors in determining the physical characteristics of agricultural products, which has also been measured and examined in this study. The moisture content of the samples during the storage period was determined using the equation (1):

$$MC\ (w.b) = \frac{w_1 - w_2}{w_1} \times 100 \quad (1)$$

where, MC represents the moisture content (wet-based), w_1 denotes the weight of the sample prior to oven drying, and w_2 signifies the weight of the following oven drying.

Another of the most important physical factors affecting the initial and direct impact on the quality of agricultural products is color. The assessment of primary color indices L^*, a^*, and b^*, along with secondary indices like color change (ΔE) derived from these primary measurements, is essential for gauging the visual quality of agricultural products throughout the storage period. To this end, primary indices were measured using the portable colorimeter model hp-200 (Shenzhen Handsome Technology Co., Ltd.), and secondary indices were calculated using the equation (2) (Gholami *et al.*, 2020; Gholami, Ahmadi, & Farris, 2017):

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (2)$$

Chemical properties

pH and TSS

Examining the chemical properties is crucial in determining the freshness and health of agricultural and food products. Among these properties, pH levels and total soluble solids (TSS) are crucial factors. The samples underwent crushing and homogenization, followed by passage through a 40µm filter paper to measure pH and TSS. The resulting extract was employed for factor measurement (Gholami *et al.*, 2023; Heydarian, Ahmadi, Dashti, & Normohammadi, 2022). A pH meter with an accuracy of 0.01 (PHS3-WB, Bante) was used for pH measurement, while a refractometer (PAL-2) was utilized for TSS measurement.

Lycopene and total phenolic content

To assess the lycopene content, an initial solution was prepared by combining 5 mL of 95% ethanol (C_2H_5OH), 5 mL of pure acetone (C_3H_6O), and 10 mL of hexane (C_6H_{14}). Subsequently, 0.4 to 0.6 g of tomato samples were added to a container containing the extraction solution. The solution was mixed with a shaker at 180 rpm for 15 minutes to achieve homogeneity. Next, 3 mL of distilled water (H_2O) was added to the samples, and they were shaken under the same conditions for 5 minutes. Following this, the samples were left undisturbed in the laboratory environment for 5 minutes to allow the phases to separate. The upper hexane phase was carefully separated, and the absorbance of the sample at a wavelength of 503 nm was measured using a spectrophotometer (Unico 2100 UV-Vis) (Fish, Perkins-Veazie, & Collins, 2002).

The Folin-Ciocalteu method was employed to measure the total phenolic content. Initially, 5 g of tomato tissue was extracted with 3 mL of 85% methanol. Subsequently, 300 µL of the extract was added to 1500 µL of 10% Folin-Ciocalteu reagent and left in the laboratory environment for 5 minutes. Then, 1200 µL of 7% sodium carbonate (Na_2CO_3) and 600 µL of distilled water (H_2O) were added, and the mixture was shaken at 110 rpm at room temperature for 90 minutes. Finally, the sample absorbance was measured at a wavelength of 765 nm using a spectrophotometer (Unico 2100 UV-Vis) and reported as milligrams of gallic acid per gram of sample tissue, based on comparison with a gallic acid standard (Singleton & Joseph A. Rossi, 1965).

Mechanical properties

Standard compression and puncture tests are commonly employed to assess the mechanical properties of agricultural products. In this research, a puncture test was used to evaluate the outermost tissue of tomatoes. To achieve this, an agricultural product testing machine (Bbt1-Fro.5th. D14, Zwick-Roell) equipped with a load cell (X Force Hp, nominal force: 500 N) and a 5 mm diameter probe loaded at a rate of 10 mm min^{-1} was utilized (Gholami *et al.*, 2017). To assess the external tissue of the product, the probe was inserted into the sample to a specified depth (5% of the diameter of each sample), and the modulus of elasticity and maximum force were recorded.

Statistical analysis

After conducting all the experiments, the data underwent evaluation. The influence of ultrasound, packaging type, atmosphere within the packages, storage temperature, and storage duration on the physical, chemical, and mechanical properties was investigated. Tests performed in triplicate were analyzed using SPSS 20 software and factorial analysis in a completely random design. This section utilized ANOVA variance analysis and Duncan's mean comparison. Additionally, relevant graphs were plotted using Excel 2013 software.

ANNs modelling

In structure of ANNs model, there are three groups of neurons; input, hidden, and output that are placed into input, hidden and output layers. The layers are connected with a transfer function. In back propagation method, inputs and outputs are related by adjusting the weights and biases, in such a way that the prediction error is minimized. The design of the system requires the selection of transfer functions of the hidden and output layer, the training algorithm, data transformation approaches, number of nerouns in hidden layer, and selection of performance measures. In this research, a three-layer feed forward neural network has been used (Fig. 1). The ANN had five inputs with normalized data: day, temperature, film, atmosphere, and ultrasound. The output layer had eleven neurons for predicting O_2, CO_2, L*, a*, b*, TSS, pH, ΔE, BI, F_{max}, and E. The hyperbolic tangent (tansig) and the linear (purelin) transfer functions were used in the neurons of the hidden and output layers, respectively. The Levenberg-Marquardt training algorithm was employed to train the network. Mean squared error (MSE) was used as the performance function to find the optimal architecture for the neural network. During the training of the network, various configurations of neuron counts in the hidden layer were assessed alongside the corresponding mean squared error (MSE). In this work, an MSE of 10-8, a minimum gradient of 10-10 and maximum epoch of 1000 were used. The initial weights and biases of the network were generated by using netint function by the program. The values of learning rate and momentum coefficient were 0.02 and 0.9, respectively. Best numbers of neurons for hidden layer were selected based on trial and error. The data were divided into two subsets: 75% was used for training, and the remaing 25% were used for testing.

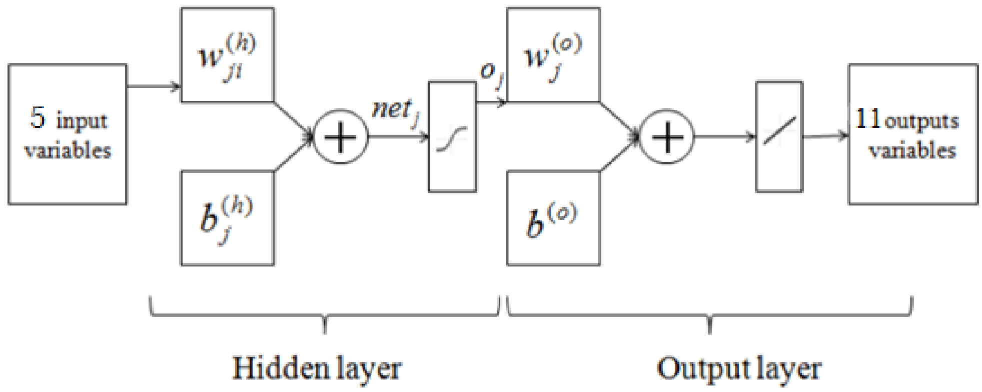
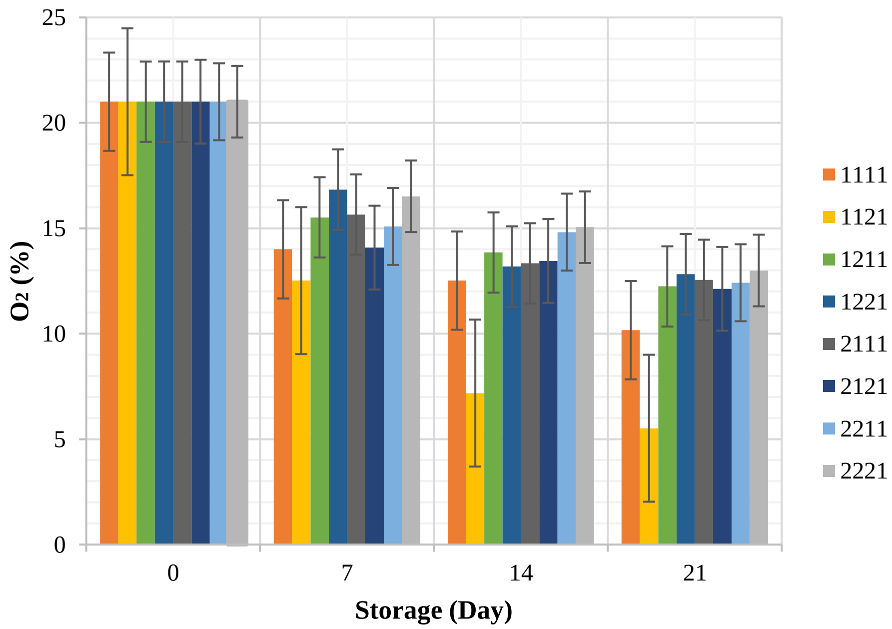


Fig. 1. Schematic representation of the artificial network model

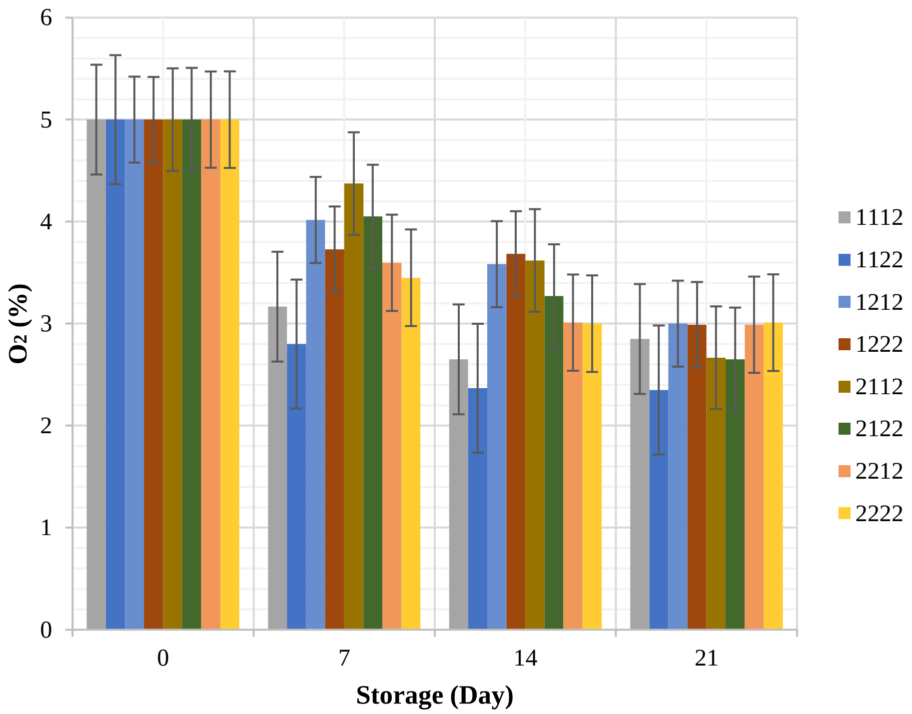
Results and Discussion

Changes in headspace gases during storage

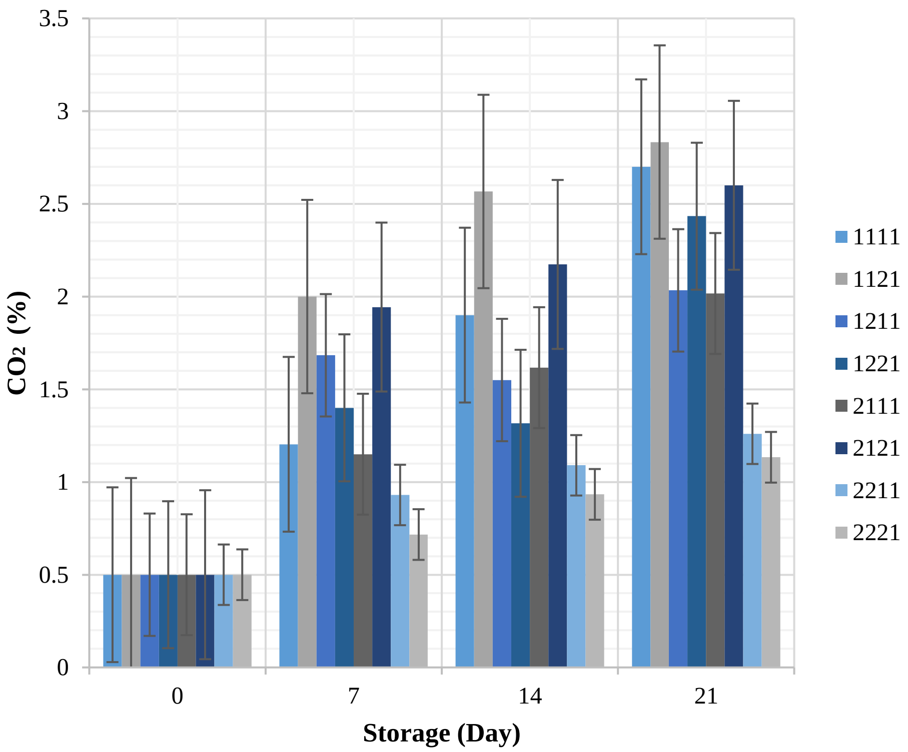
The changes in O_2 and CO_2 gases inside the packages during the storage period for all treatments are illustrated in Fig. 2. In all treatments, a trend of decreasing O_2 levels and increasing CO_2 levels inside the packages was observed during the storage. This is because of the resperation of tomatos. Similar results of gas changes inside packaging for various agricultural products have also been reported by other researchers (Castellanos, Cerisuelo, Hernandez-Muñoz, Herrera, & Gavara, 2016; D'Aquino *et al.*, 2016; Paulsen, Barrios, & Lema, 2019). The study of changes in CO_2 in MAP packages showed a declining trend in this factor on the first 7 days for all packages with PE film (packages with codes: 1112, 1212, 2112, and 2212). The reason for this is that the injection of 3% CO_2 into MAP packages was much higher than the ambient CO_2, and the high gas permeability of ordinary films allowed for CO_2 to transferred from the inside of the package to the outside during the first 7 days. Nonetheless, after the initial 7 days, the ongoing respiration and carbon dioxide production by the tomatoes led to an increase in the CO_2 levels in these packages as well. At the end of the storage period, upon analyzing the extent of changes in all samples, it was determined that the highest changes in O_2 levels occurred in packages with code 1121, with a percentage of 73.73%, while the lowest changes occurred in packages with code 2212, at 39.80%. Additionally, the analysis of CO_2 found that the highest changes occurred in package 1121, while the lowest changes occurred in package 1212. These results indicate that storage temperature and the atmosphere within the packages played a role in controlling respiration within the packages and, consequently, gas changes (Tavar, Rabbami, Gholami, Ahmadi, & Kurtulmus, 2024). Furthermore, due to its varying permeability to gases, the type of packaging film also influenced the significant gas changes (D'Aquino *et al.*, 2016). As the results demonstrated, the most significant changes were observed in packages with nanofilms, which could be attributed to the impermeability of these films to O_2 and CO_2 gases in such a way that O_2 reduction and CO_2 accumulation would occur with product respiration (Gholami *et al.*, 2020). This confirmation was further substantiated through statistical analysis and the execution of an analysis of variance on the obtained data. The results of the analysis of variance (Table 2) showed that all independent factors (day, ultrasonic treatment, storage temperature, film type, and the atmosphere inside the package) and their interactions had a significant effect ($p < 0.01$) on the gas changes within the packages. Furthermore, the results of Duncan's means comparison between different days indicated that variations between different days were also significant.



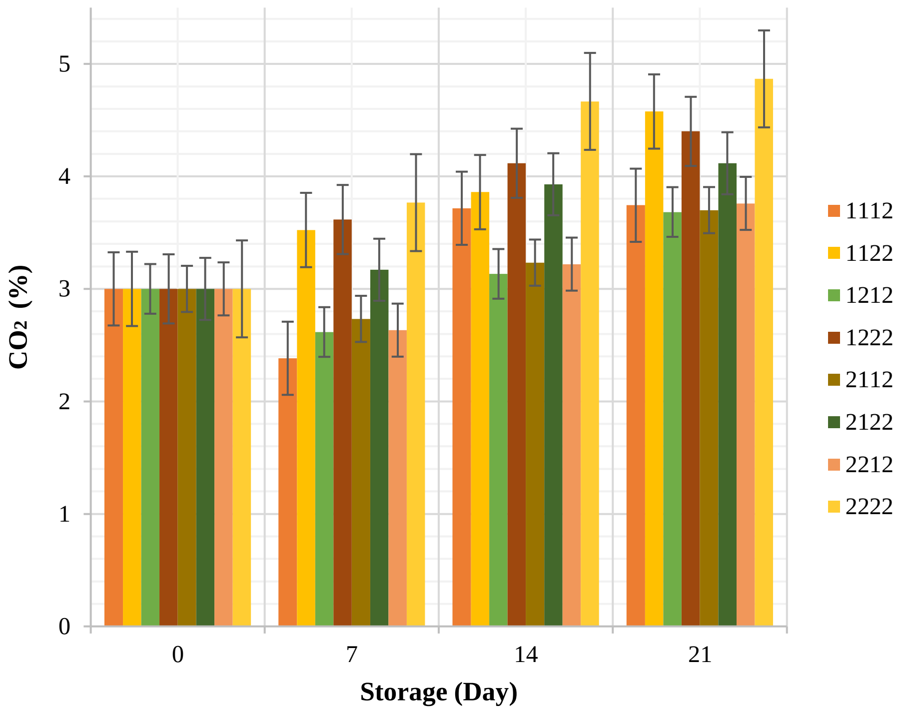
(a)


O2 (%)
Storage (Day)
0
7
14
21
0
1
2
3
4
5
6
1112
1122
1212
1222
2112
2122
2212
2222

(a')


CO2 (%)
Storage (Day)
0
7
14
21
0
0.5
1
1.5
2
2.5
3
3.5
1111
1121
1211
1221
2111
2121
2211
2221

(b)



(b')

Fig. 2. (a & a') O_2 and (b & b') CO_2 changes during storage in ambient (codes ending in 1), and MAP (codes ending in 2) atmospheres

Table 2- Variance Analysis of physical properties and gas composition

Source of Changes	df	Moisture	L*	a*	b*	ΔE	BI	O_2	CO_2
D	3	32.76**	66.84**	107.74**	14.62**	293.93**	513.52**	429.45**	22.29**
U	1	0.42 ^{ns}	5.34*	4.20 ^{ns}	0.001 ^{ns}	1.79 ^{ns}	8.77 ^{ns}	33.95**	1.98**
T	1	10.83**	2.69*	354.58**	4.67**	5.75*	1106**	62.70**	2.58**
F	1	61.98**	27.36**	15.65**	20.87**	100.14**	138.02**	9.16**	10.52**
A	1	0.001 ^{ns}	0.06 ^{ns}	3.32 ^{ns}	20.87**	64.73*	231.82*	8342**	272.15**
D*U*T*F*A	3	1.18**	9.47**	86.57**	5.25**	15.01**	323.68**	1.66**	0.21**
Error	192	0.16	0.63	1.61	0.62	1.28	13.74	0.25	0.02

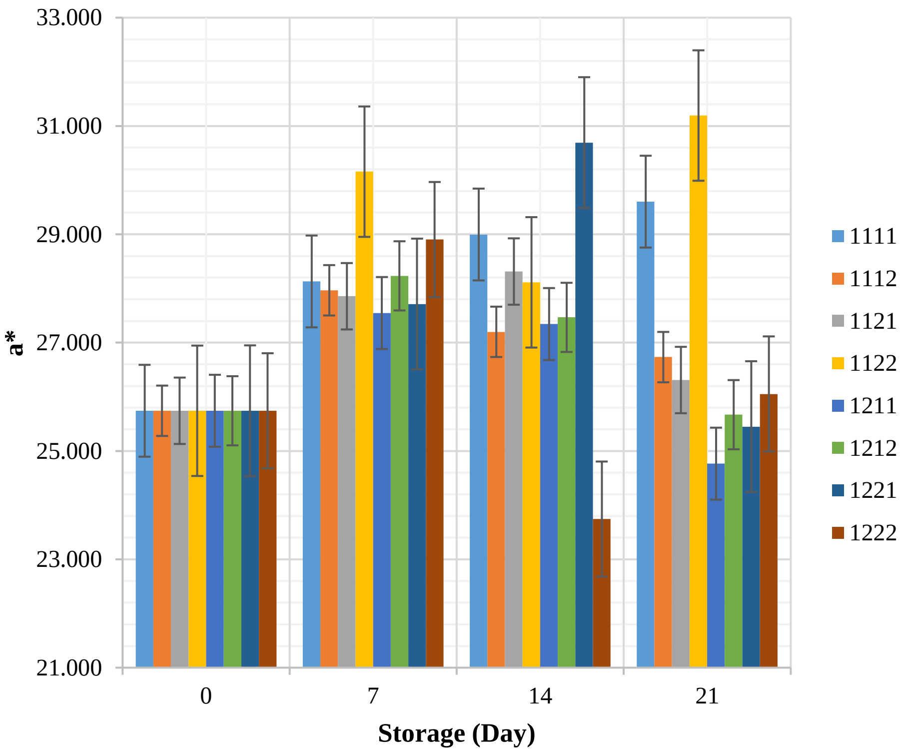
D = Day, U = Ultrasound, T = Temperature, F = Film, A = Atmosphere

^{ns} not significant, * significant at 95% level, ** significant at 99% level

Changes in physical and appearance properties during storage

The alterations in the physical and appearance properties of the samples throughout the storage duration are delineated in Fig. 3. The investigation of moisture parameters during the storage period across all treatments reveals a consistent decrease in this factor across all samples. A decline in moisture content invariably results in a commensurate reduction in the weight of agricultural products. Consequently, as the reduction in moisture content of agricultural products intensifies, it not only gives rise to factors such as wrinkling, signifying a decline in product quality, but also contributes to a decrement in economic value. Other scholarly investigations have documented comparable weight loss findings in agricultural products (Osae *et al.*, 2022; Zhao *et al.*, 2023). Upon a comprehensive examination of the results after the storage period, it is evident that the most substantial decrease in moisture content occurred in samples designated as 1111, registering a reduction of 3.81%. Conversely, the most marginal reduction in moisture content was observed in samples labeled as 2222, with a decrease of 1.07%. Furthermore, across various treatment groups, the alterations discerned in samples enclosed within Nano films were less pronounced than those enveloped in conventional polyethylene (PE) films. This discrepancy can be attributed to nanofilms' superior water vapor impermeability, which retains moisture within the packages. However, it is imperative to acknowledge that the equilibrium between moisture preservation and loss in packaged agricultural products must be carefully upheld. Excessive moisture loss and the escape of moisture from the confines of the packaging can lead to weight loss, wrinkling, and an expedited aging process for the product. Conversely, an absence of moisture exchange with the external environment can result in an overabundance of moisture accumulation within the package, consequently hastening the spoilage process of the product. The result of variance analysis showed that all treatments except ultrasound and atmosphere had a significant effect on moisture (Table 2). The reason why the type of packaging film has a significant effect on moisture changes is directly due to the difference in water vapor permeability between PE film and nano film, such that the accumulation of humidity in the nano film maintains the moisture of the tomatoes during the storage period (Gholami *et al.,* 2017). This can also cause changes in other physical and mechanical parameters, which have been evaluated in the relevant sections.

A paramount factor that profoundly influences Consumers' selection of agricultural products is the color of the commodities (Zhao *et al.,* 2023). Consequently, a meticulous examination was undertaken to scrutinize appearance attributes, encompassing color indices (L*, a*, b*) and color change during storage. The findings illuminate a decrease in the L* value, an increase in the a* value across most treatments, and an overall rise in the ΔE value across all treatments (Figure 3). The escalation in a* values signifies an intensification of the redness of the product over the storage period. This effect is considered favorable for products harvested prematurely but can engender detrimental consequences following full ripening, such as hastening the aging and deterioration of the product, partly attributable to the conversion of chloroplasts in tomato products (Taye, Tilahun, Seo, Park, & Jeong, 2019; Tilahun *et al.,* 2021). As detailed in Table 2, almost all treatments have a pronounced impact on alterations in the color indices during storage. Moreover, a comparative analysis utilizing Duncan's mean comparison method between days 0, 7, 14, and 21 underscores the substantial disparities in changes in brightness index and color variations among the different time points. The results manifest that the most notable fluctuations in the brightness index (L*) amounted to 6.85%, while the most negligible changes were a mere 0.09%, manifesting in samples coded as 2112 and 1222, respectively. As for the green/red index (a*), the most substantial shifts were documented at 32.10%, while the most modest alterations were recorded at 0.52%, observed in samples denoted as 2111 and 2222, correspondingly. Previous research endeavors have yielded congruent outcomes regarding shifts in color indices during storage (Fan, Zhang, & Jiang, 2019; Tilahun *et al.,* 2021; Zhao *et al.,* 2023). Observing minimal variations in samples stored under modified atmospheric conditions and refrigeration underscores these treatments' significant and favorable impact in safeguarding the initial product quality throughout the storage period.


33.000
31.000
29.000
27.000
25.000
23.000
21.000
a*
0
7
14
21
Storage (Day)
1111
1112
1121
1122
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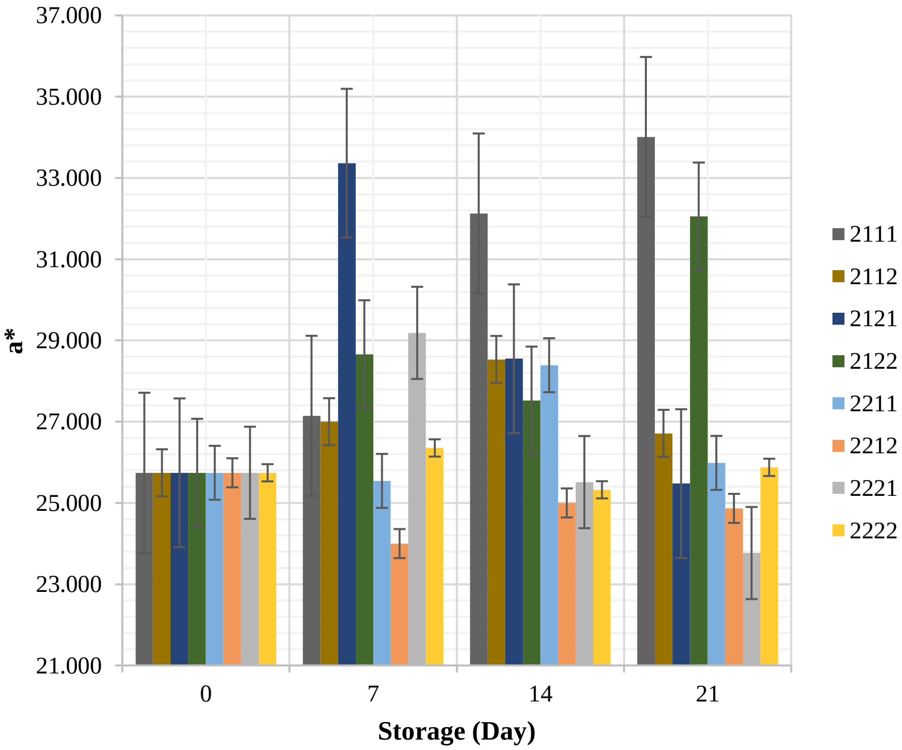
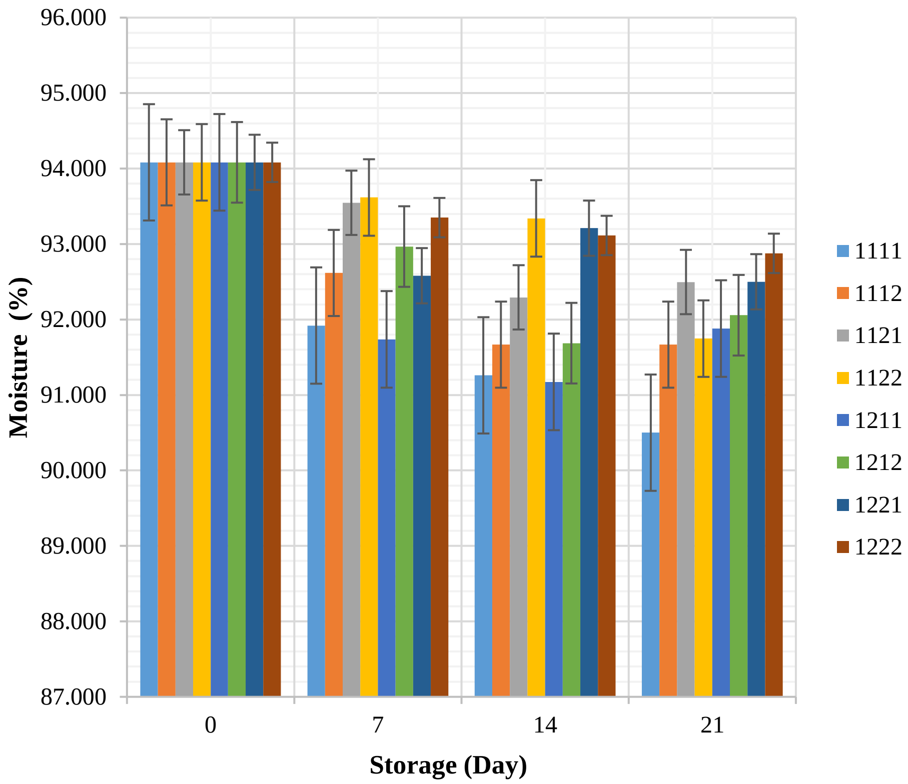
1212
1221
1222

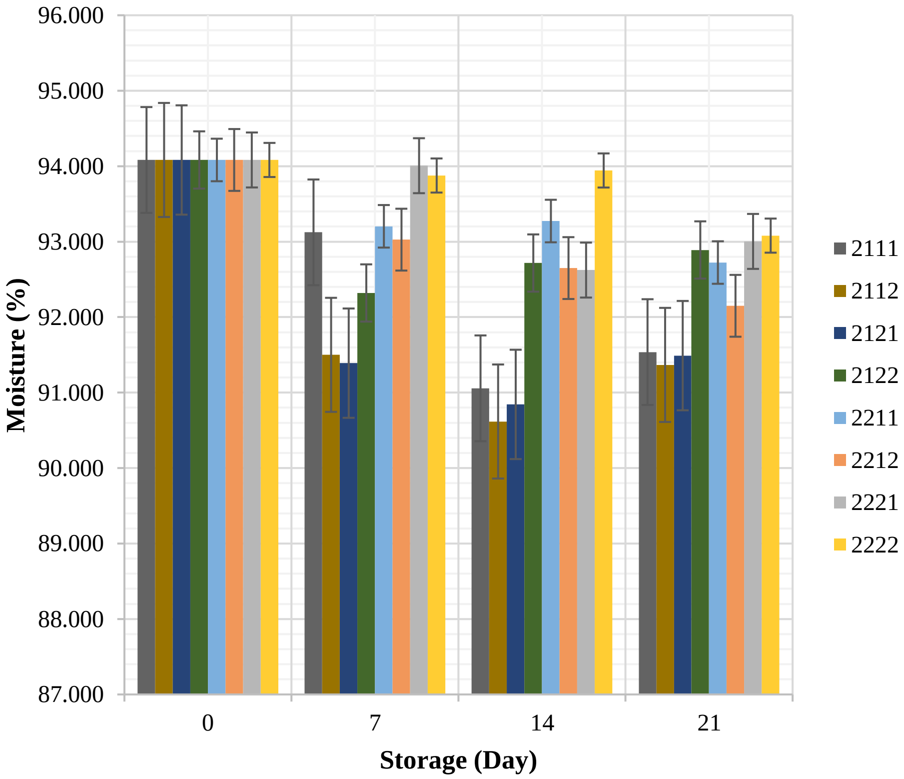
(a)


37.000
35.000
33.000
31.000
29.000
27.000
25.000
23.000
21.000
a*
0
7
14
21
Storage (Day)
2111
2112
2121
2122
2211
2212
2221
2222

(a')



(b)

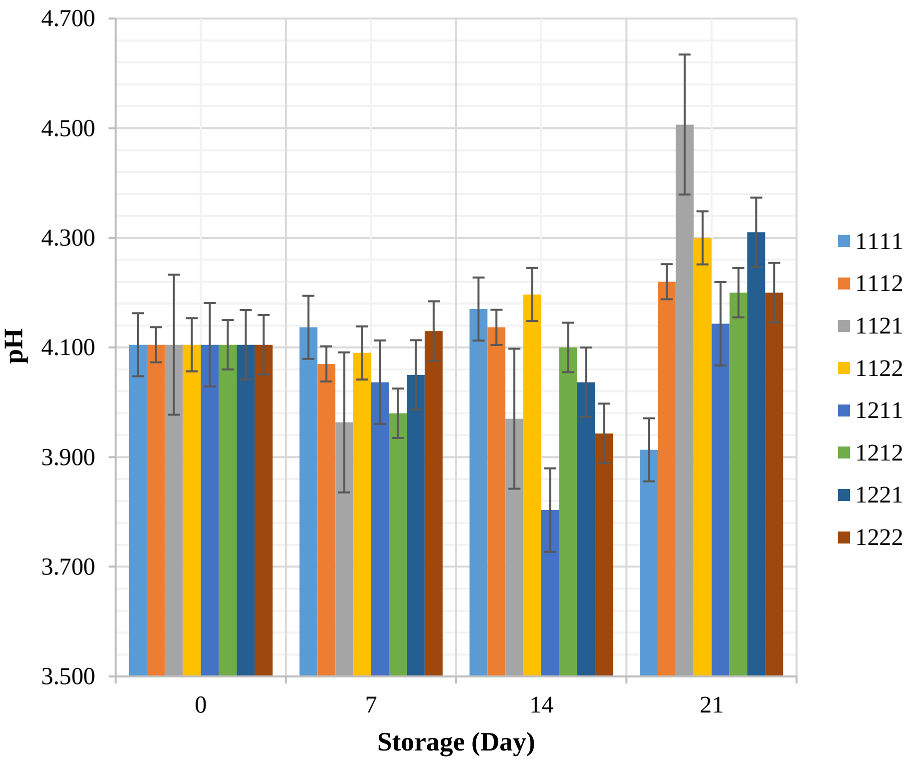


(b')

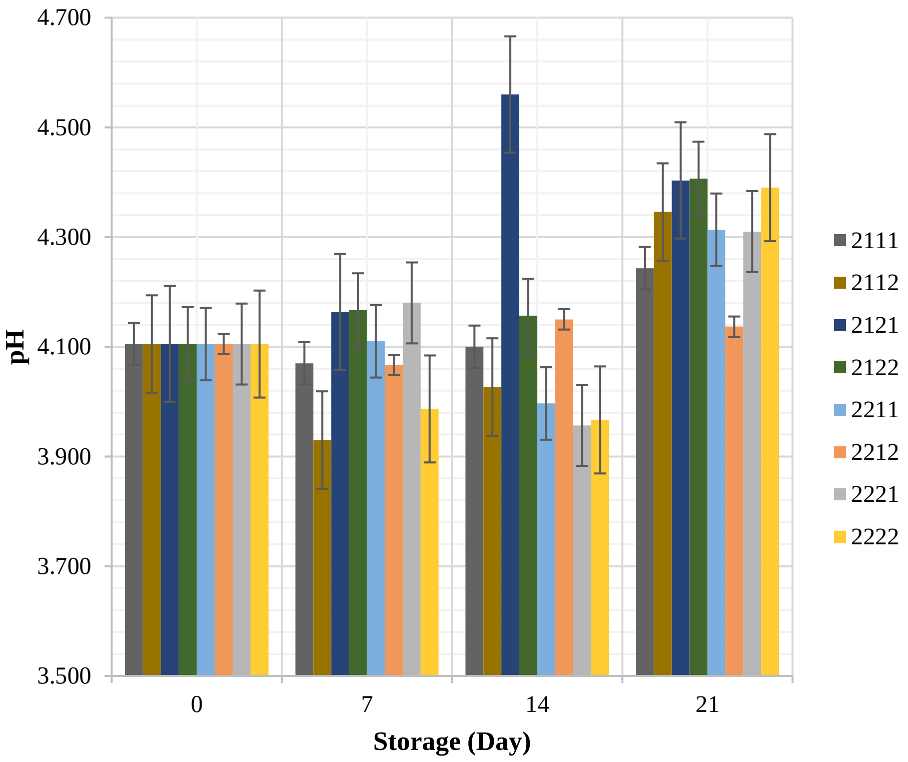
Fig. 3. Physical properties change during storage with (codes starting with 2) and without (codes starting with 1) ultrasound treatment: (a & a') a*, and (b & b') moisture

Changes in chemical properties during storage

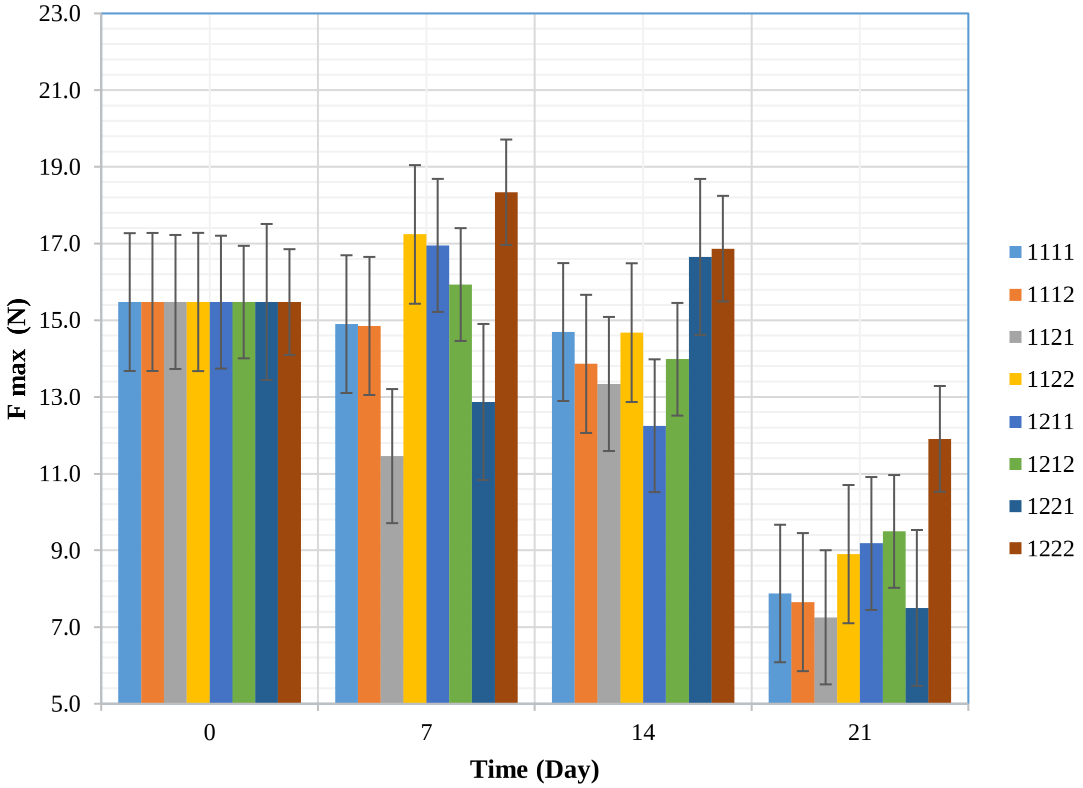
Chemical properties, such as pH, play a vital role in evaluating the quality of agricultural and food products (Cai, Zhong, Ma, Yang, & Sun, 2022). Conversely, TSS is a crucial indicator for assessing tomato ripening. Variations in TSS during the natural ripening process, attributed to the hydrolysis of starch into sugars, are noteworthy (Kaewklin, Siripatrawan, Suwanagul, & Lee, 2018). Examination of the pH data reveals a gradual increase over the storage period in all treatment groups, especially between the first and last days of the period (Fig. 4), whereas a consistent trend in TSS alterations during storage remains elusive. Statistical data analysis indicates that all treatments significantly influence pH and TSS fluctuations, except temperature on TSS changes (Table 3). Other researchers have also reported similar pH fluctuations (Álvarez-Hernández, Martínez-Hernández, Castillejo, Martínez, & Artés-Hernández, 2021; Lan, Zhang, Ahmed, Qin, & Liu, 2019). Metabolic processes involving the utilization of sugars and organic acids are likely contributors to pH fluctuations during storage (Lan *et al.*, 2019). Ultimately, after the storage period, the most significant pH changes were observed in sample 1121, registering a 9.78% increase, while the most minor pH variations occurred in sample 2212, with only a 0.77% shift. Furthermore, the most pronounced changes in TSS were evident in sample 1112, exhibiting a substantial 16.07% shift, while the most minor changes were observed in sample 1222, with a mere 2.16% adjustment. The purpose of packaging fresh products is to control their characteristics during the storage period. Therefore, as a general result of this section, samples stored under refrigeration conditions with a modified atmosphere exhibit controlled pH and TSS changes during storage.



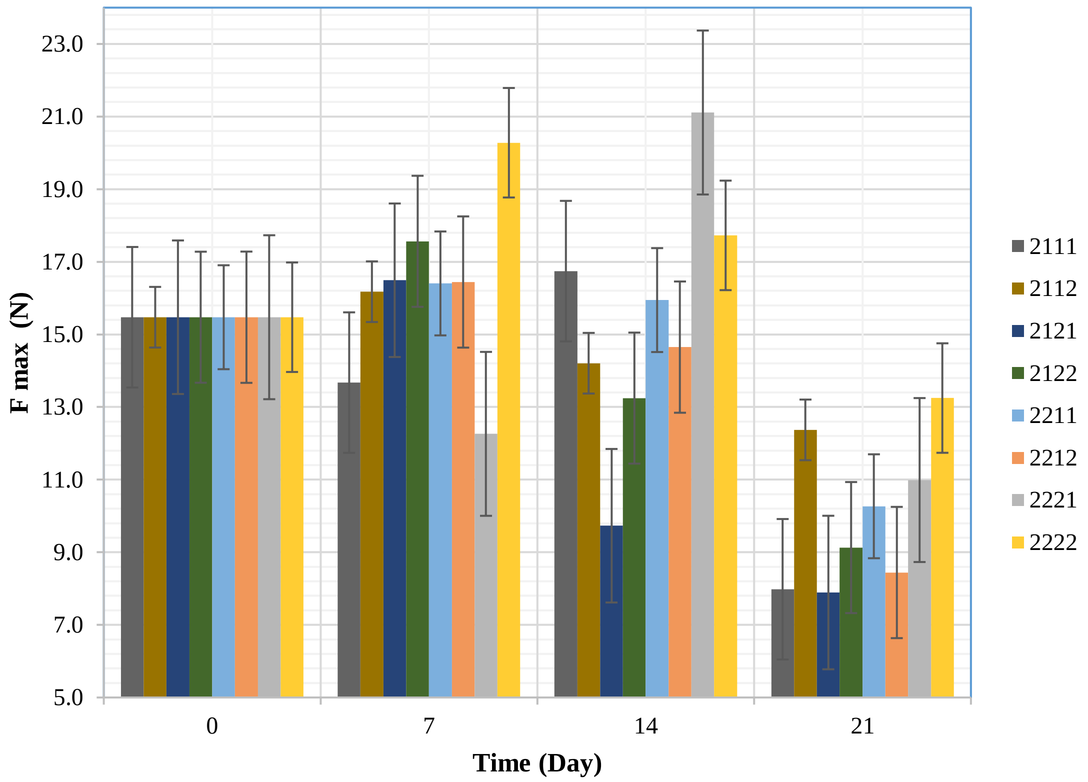
(a)


4.700
4.500
4.300
4.100
3.900
3.700
3.500
pH
0
7
14
21
Storage (Day)
2111
2112
2121
2122
2211
2212
2221
2222

(a')


23.0
21.0
19.0
17.0
15.0
13.0
11.0
9.0
7.0
5.0
F max (N)
0
7
14
21
Time (Day)
1111
1112
1121
1122
1211
1212
1221
1222

(b)



(b')

Fig. 4. Changes in: (a) pH, and (b) mechanical properties during storage; with (codes starting with 2) and without (codes starting with 1) ultrasound treatment

Table 3- Variance Analysis of chemical and mechanical properties

Source of Changes	df	pH	TSS	F_{max}	E
D	3	0.65^{**}	1.61^{**}	576.52^{**}	29.37^{**}
U	1	0.20^{**}	4.34^{**}	37.08^{**}	5.07^{**}
T	1	0.20^{**}	0.01^{ns}	89.25^{**}	0.15^{ns}
F	1	0.39^{**}	15.71^{**}	8.61^{*}	5.95^{**}
A	1	0.00^{*}	1.39^{**}	76.80^{**}	13.98^{**}
D*U*T*F*A	3	0.07^{**}	14.47^{**}	8.33^{**}	0.64^{**}
Error	192	0.00	0.06	1.76	0.09

D = Day, U = Ultrasound, T = Temperature, F = Film, A = Atmosphere

^{ns} not significant, * significant at 95% level, ** significant at 99% level

The pigments found in tomatoes primarily consist of chlorophyll a, chlorophyll b, beta-carotene, and lycopene, which undergo metabolic processes during the ripening of tomatoes (Fagundes *et al.*, 2015). In this study, the investigation focused on phenolic content and lycopene as key chemical factors. The initial phenolic content and lycopene levels were 1083.26 (mg GAE/kg) and 9.15 (mg/100g). By the end of the storage period, the most significant changes (reduction) in lycopene content were observed in sample 2121, with a decrease of 76.13%, whereas the lowest changes (reduction) were evident in samples 2221, showing a decrease of 24.98%. Across all samples, the trend in lycopene changes consistently decreased, in alignment with similar findings reported by Olveira-Bouzas *et al*. regarding lycopene changes during storage (Olveira-Bouzas *et al.*, 2021). Increasing lycopene in unripe products can lead to elevated ethylene production and ripening. Conversely, controlling lycopene changes during storage in ripe products can influence the regulation of the aging process (Sangwanangkul *et al.*, 2017; Walubengo *et *al.*, 2022). Therefore, during storage, the focus should be on controlling the changes of lycopene using different packaging methods, as was done in this research.

Phenolic compounds are primary antioxidant compounds commonly found in agricultural products (Cai *et al.*, 2022). The study's results indicate a decrease in the phenol content at the end of the storage period compared to the initial levels in all treatments, which is consistent with the results of other researchers (Tilahun *et al.*, 2021). Notably, the most significant reduction was observed in samples labeled as 2121, with a decrease of 69.70%, while the lowest reduction occurred in samples labeled as 2222, with a decrease of 55.2%. Overall, it was observed that the changes in the MAP samples and those stored in the refrigerator were lower compared to the other samples. In a study conducted by Toor *et al*. in 2006, it was reported that the phenol content increased at the beginning of the storage period and then decreased at the end of the storage period. In general, the increase in the total phenolic content indicates the development of the ripening of the product, especially with the increase of the phenylalanine ammonia-lyase (PAL) enzyme activity, which plays an important role in phenolics compounds synthesis. This issue plays a positive role in the storage conditions of the unripe product, but in the ripe product, the control of this factor will have a positive and effective role in maintaining the quality of tomatoes.

Changes in mechanical properties during storage

Another critical aspect affecting the quality and marketability of food and agricultural products is their mechanical properties and texture. This study conducted a puncture test to assess product texture, measuring the maximum force and elastic modulus. The results showed decreased maximum penetration force (Fig. 4) and elastic modulus during storage. Similar findings have been reported for the decrease in penetration force and elastic modulus of various products during storage (Gholami *et al.*, 2020; Paulsen *et al.*, 2019). Maximum penetration force reflects tissue firmness, with the product's tissue firmness indicating cell-to-cell adhesion (Fan *et al.*, 2019). At the end of the storage period, it was found that the most significant reduction in maximum penetration force occurred in samples labeled as 1121, with a decrease of 53.14%, while the minimum reduction was observed in samples labeled as 2222, with a decrease of 14.39%. Furthermore, the analysis of variance results indicated that all treatments had a significant effect at the 1% and 5% levels on changes in the penetration force. Additionally, all treatments except temperature impacted changes in elastic modulus (Table 3). An examination of the extent of mechanical changes (reductions) during the storage period revealed that the combination of modified atmosphere, ultrasound treatment, and storage at 4°C positively influenced the product's texture. This effect was also statistically significant; other researchers have reported similar opinions (Paulsen *et al.*, 2019). The impact of the modified atmosphere may be attributed to the active control of detrimental enzymatic activities in the cell wall by regulating oxygen (O_2) levels available to the product. The control of enzymatic activities in agricultural products leads to the control of the aging process. The result of this will be to keep the internal and external texture of the product younger and thus prevent the reduction of the modulus of elasticity and penetration force. Keeping the texture of the product fresh will also have a direct effect on the resistance of the product in the post-harvest stages, including transportation, as well as increasing marketability.

Results of ANN analysis

In order to minimize ANN training time, only one hidden layer was considered. With this configuration, the best network was found with 5-10-11 topology, i.e., a network having 10 neurons in the hidden layer. R^2 and RMSE for the best ANN model are shown in Table 4. The results showed the proper prediction of some parameters using ANN. E and L* were not predicted properly by ANN, whereas O_2

and CO_2 were predicted with high accuracy, which has shown the accurate performance of the ANN in predicting the data with the selected structure.

Table 4- Performance statistics of the ANN model for properties estimation based on different statistical indicators

	O_2	CO_2	L^*	a^*	b^*	ΔE	BI	pH	TSS	F_{max}	E
R^2	0.931	0.865	0.406	0.514	0.582	0.607	0.721	0.507	0.501	0.581	0.305
RMSE	1.46	0.44	1.66	2.75	1.18	2.29	3.10	0.15	0.64	2.48	0.003

Conclusion

Utilizing innovative methods for packaging and preserving agricultural and food products can significantly impact maintaining product quality and extending their shelf life. These pioneering techniques encompass ultrasonic irradiation, temperature control, specialized packaging films, and modified atmospheres. The collective utilization of these methods has demonstrated a noteworthy positive influence on the properties of tomatoes throughout the storage duration. In a comprehensive analysis, it has been ascertained that the application of modified atmospheres (5% O_2 + 3% CO_2 + 92% N_2), coupled with precise temperature regulation, exerts a constructive and substantial influence on the preservation and management of the initial attributes of tomatoes. Nonetheless, it is essential to recognize that deploying nanofilms can yield diverse outcomes. While they can enhance certain aspects, their impermeability to oxygen (O_2), carbon dioxide (CO_2), and water vapor can, in certain circumstances, engender adverse effects. Furthermore, ultrasonic irradiation has proven beneficial in governing specific tomato properties during storage. Given the inherent variability in the post-harvest behavior of agricultural products, it is advisable to tailor the deployment of modified atmospheres to the distinct characteristics of each product when packaging agricultural and food items. On the other hand, the results showed that the use of ANN in predicting some properties can be used with high accuracy.

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Conflicts of interest: All authors declare that there is no conflict of interest.

Authors Contribution

R. Gholami: Conceptualization, Methodology, Data acquisition, Data pre and post processing, Statistical analysis, Software cervices, Numerical/computer simulation, Validation, Visualization, Text mining, Draft Writing, Review and editing services

A. Nourmohammadi: Methodology, Data acquisition, Data pre and post processing, Statistical analysis

E. Ahmadi: Conceptualization, Methodology, Technical advice

H. Rabbani: Conceptualization, Methodology, Technical advice

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خواص مهندسی گوجه‌فرنگی تحت تاثیر تابش التراسونیک و شرایط بسته‌بندی در طول دوره نگهداری

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چکیده

در این پژوهش تابش التراسونیک (US)، نوع فیلم بسته‌بندی، کنترل اتمسفر داخل بسته‌ها و کنترل دمای نگهداری به‌منظور انبارداری گوجه‌فرنگی مورد استفاده قرار گرفت. نیمی از نمونه‌ها تحت تابش التراسونیک قرار داده شدند و سپس با استفاده از فیلم پلی‌اتیلن (PE) و پلی‌اتیلن مجهز به ۲٪ ذرات نانو رس (نانو فیلم) تحت شرایط اتمسفر معمولی و اتمسفر اصلاح‌شده ($5\%\ O_2 + 3\%\ CO_2$) بسته‌بندی شدند. نمونه‌ها در دماهای ۲۵ درجه سلیسیوس و ۴ درجه سلیسیوس و به مدت ۲۸ روز نگهداری شدند. در طول دوره نگهداری خواص فیزیکی شامل: رطوبت و شاخص‌های رنگ، خواص شیمیایی شامل: pH، مواد جامد محلول (TSS)، لیکوپن و فنل کل و خواص مکانیکی شامل نیروی نفوذ و مدول الاستیسیته به‌صورت هفتگی ارزیابی شدند. نتایج نشان داد که دوره نگهداری اثر مخربی بر روند تغییرات خواص داشته است. استفاده از اتمسفر اصلاح‌شده، دمای مناسب ذخیره‌سازی، و استفاده از تیمار اولتراسونیک و نانوفیلم به‌طور موثری سبب حفظ کیفیت محصول و کنترل خواص آن می‌شوند. نتایج تحلیل آماری نشان داد که تیمارهای مورد استفاده تاثیر موثری در سطح ۱٪ و ۵٪ بر اکثر خواص اندازه‌گیری‌شده داشته‌اند. از طرف دیگر شبکه عصبی مصنوعی (ANN) به‌منظور پیش‌بینی داده‌ها مورد استفاده قرار گرفت و مشخص شد که بهترین ساختار برای پیش‌بینی خواص فیزیکی، مکانیکی و شیمیایی گوجه‌فرنگی ۵-۱۰-۱۱ بوده است. اکسیژن و دی‌اکسید کربن با دقت بالایی (ضریب همبستگی ۰/۹۳ و ۰/۸۶) پیش‌بینی شدند که نشان از عملکرد مناسب شبکه عصبی مصنوعی در پیش‌بینی این پارامترها با ساختار معرفی‌شده دارد.

واژه‌های کلیدی: التراسونیک، انبارداری، بسته‌بندی، گوجه‌فرنگی

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