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MAGNETIZED WATER AS A NON-THERMAL PRESERVATION METHOD FOR ORANGE DRINK: COMPARATIVE INSIGHTS AGAINST PASTEURIZATION AND CHEMICAL PRESERVATIVES

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ABSTRACT. Orange beverages are popular but susceptible to nutrient loss and microbial spoilage during storage. Pasteurization ensures microbiological safety, but reduces bioactive compounds; therefore, there is a need for alternative preservation methods. In this study, pasteurization (OD1), sodium benzoate (OD2), and magnetized water treatment (OD3) were compared with a control (C) for orange drinks stored at 5 °C for 15 days. Vitamin C decreased considerably in the control (51.5% decrease), whereas OD1, OD2, and OD3 limited the reduction to 5.0%, 27.5%, and 25.9%, respectively. The same trend of protection was noticed for TPC and antioxidant activity in OD2 and OD3. Microbial levels exceeded in C on day 6, whereas OD2 and OD3 remained below 3 log CFU/mL at day 15. Sensory evaluation recorded great consumer acceptability, with OD3 comparable to OD1. These results indicate that magnetized water is a non-thermal technology that extends shelf life without compromising quality.

KEY WORDS: Magnetic field, Citrus beverage, Vitamin C, Color, Shelf-life, Microbiological stability

INTRODUCTION

Citrus sinensis, also known as the Baladi orange, is among Egypt's most prized cultivars, highly sought after in the drink and juice markets for its high juice content, fragrant aroma, and sweet-to-acid ratio [1]. Apart from its economic value, *Citrus sinensis* is a rich source of bioactive compounds that have significant health benefits. It is a good source of vitamin C, a potent antioxidant, and carotenoids, which contribute to its rich color. The fruit is particularly rich in flavonoids, such as hesperidin and narirutin, which are reported to possess potent antioxidant and anti-inflammatory activities [2]. Scientific studies suggest that such chemicals may play a significant role in maintaining cardiovascular health by helping to regulate blood pressure and cholesterol, and possibly affording protective effects against many chronic diseases [3].

Orange drinks (OD), which are citrus beverages made from orange juice, water, sugar, and possibly flavorings or preservatives, are widely consumed. Due to their high antioxidant and vitamin C content, these drinks are often referred to as functional beverages and are enjoyed for their refreshing flavor and affordability [4]. However, due to their relatively high water content, acidity, and sugar levels, they are prone to oxidative rancidity, enzymatic hydrolysis, and microbial contamination during storage, leading to undesirable flavor changes [4].

In recent years, growing consumer demand for minimally processed and "fresh-like" foods has driven the development of non-thermal preservation technologies. The US FDA has approved ultraviolet-C (UV-C) treatment as a non-thermal method for disinfecting fruit juice, such as guava

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juice, using LED technology, which effectively reduces microbial burdens without compromising quality [5]. Other promising non-thermal methods are high-pressure processing (HPP), ultrasound (US), and pulsed electric fields (PEF), which can preserve sensory and nutritional qualities while ensuring microbiological safety [6].

Among these treatments, magnetic field (MF) treatment has recently been brought to the forefront due to its potential to inactivate microorganisms through heat-free damage. Pulsed magnetic fields (PMF) and static magnetic fields (SMF) have been reported to disrupt microbial membranes, alter energy metabolism, and induce physiological disorders in microbial cells [7-9]. While promising, research on MF in food processing has primarily focused on microbial inactivation, with few studies examining its effects on enzyme activity and nutritional content [10]. The most relevant to MF processing is the use of magnetized water (MW), which is created by subjecting water to a strong static magnetic field. This is believed to alter water's physicochemical properties through altering hydrogen bonds, increasing ion mobility, and reducing cluster size, and thereby enhancing nutrient diffusion and chemical interactions [11-15]. In agriculture, magnetized water has been widely reported to enhance seed germination, plant growth, and nutrient assimilation [16]. Nevertheless, its potential for use in food processing has not yet been thoroughly researched, especially for juice preservation.

Given the potential of MW as a chemical-free, non-thermal, and user-friendly tool, and the limited available literature, this study aimed to assess its effectiveness in maintaining the quality of orange juice. Therefore, the study compares the impact of magnetized water treatment, pasteurization, sodium benzoate addition, and an untreated control on microbial stability, physicochemical properties, retention of bioactive compounds (ascorbic acid and total phenolics), antioxidant capacity, and sensory properties during refrigerated storage. This work presents new data regarding the application of magnetized water as a green, non-invasive technology to improve juice quality and shelf life.

MATERIALS AND METHODS

Chemicals and reagents

Baladi oranges (*Citrus sinensis*) were purchased from Nefartete Company, Cairo, Egypt, and sugar was purchased from the local market in Giza, Egypt. The following chemicals were used: 2,2-Diphenyl-1-picrylhydrazyl (DPPH, ≥ 95%), ethanol absolute (analytical grade), Metaphosphoric acid (≥ 99%), acetic acid (glacial, ≥ 99.7%), 2,6-dichloroindophenol, sodium salt hydrate, and sulphuric acid (95-98%). Folin-Ciocalteu reagent, sodium carbonate (≥ 99%), and sodium benzoate were purchased from Sigma-Aldrich (St. Louis, MO, USA). Potato Dextrose Agar (PDA) medium was obtained from Oxoid Ltd. (Basingstoke, Hampshire, UK).

Instruments and apparatus

All instruments and equipment used in this study were specified as follows: magnetized water was generated using a Delta magnetic water treatment device (SKU: DW-DP80-2INCH, Delta Water Co., Alexandria, Egypt). The pH of the water and orange drink samples was measured using a digital pH meter (Model 3305, Jenway Ltd., Dunmow, Essex, UK). Water's viscosity was determined using a BS/U-Tube viscometer (Borosil Glass Works Ltd., Mumbai, India). Total dissolved solids (TDS) and conductivity for treated water were determined using a handheld conductivity meter (Hanna Instruments Inc., Woonsocket, RI, USA; S/N 08520147). Pasteurization was performed using a laboratory-scale stainless-steel batch pasteurizer under controlled temperature conditions (90 °C for 60 s) (locally manufactured, Cairo, Egypt). Total soluble solids (TSS) of orange drink samples were measured using a hand refractometer (Model REF103, 0–32 Brix, USA) at 20 °C. Color measurements for orange drink samples were performed using a Minolta colorimeter (Model CR-410, Konica Minolta, Inc., Tokyo, Japan). Microbiological analyses were conducted using an incubator (Model JBH000, Astell Hearson Ltd., England).

Preparation of magnetized water

The magnetized water was generated using a Delta magnetic water treatment device with a reported magnetic field intensity of 1.5 Tesla, produced by a static magnetic field generated by a stainless steel housing. The device was incorporated into a continuous water-flow system, with a flow rate of 11-45 m^3/h. The water was exposed to the magnetic field as it flowed, with exposure time determined by the flow rate and the device's dimensions. The treated water was collected as it left the device and used without storage to prevent loss of the magnetic effect.

Evaluation of magnetized water

pH

The pH of the water samples was measured with a calibrated digital pH meter. A 50 mL aliquot of the water sample was placed in a clean beaker for each measurement. A minute was allowed for the reading to stabilize before recording. This measurement was performed in triplicate for each sample to ensure accuracy [17].

Total dissolved solids and conductivity

Total Dissolved Solids (TDS) were measured with a handheld conductivity meter. Before measurement, the instrument was set according to the manufacturer's instructions. The meter probe was cleaned with deionized water, then placed in each sample solution until a stable reading was obtained. The electrical conductivity (EC) value was measured in mS/cm, and the TDS value in mg/L.

Preparation of orange drink

An orange drink was prepared in four treatments: control (C), pasteurized (OD1), sodium benzoate (OD2), and magnetic field (OD3). Freshly extracted orange juice was mixed with water (tap or magnetized) and sugar at a 2:1 juice-to-water ratio, and the mixture was brought to 14-16 Brix in all instances. Pasteurization was performed using a stainless-steel batch pasteurizer with precise temperature control at 90 °C for 60 s [5]. Then the bottles were cooled. The sodium benzoate treatment was prepared by blending 0.1% of the preservative, calculated on a mass basis. The prepared samples were filtered through a stainless steel screen (0.5-1 mm pore size) to remove pulp, then filled into sterilized glass bottles. The samples were refrigerated at 5-7 °C for 15 days, during which physicochemical and microbiological analyses were performed at 0, 3, 6, 9, 12, and 15 days.

Estimation of physicochemical properties of orange drink

pH

The pH values of the orange drink samples were determined according to Ali *et al.* [5] using a digital pH meter.

Total soluble solids

The total soluble solids (TSS) of the orange drink were measured using a hand refractometer at 20 °C.

Viscosity

Water viscosity was measured with an Ostwald capillary viscometer. The viscometer was immersed in a thermostatic water bath at 25 ± 0.1 °C, filled with distilled water, and the efflux time between calibration marks was measured. Kinematic viscosity (ν) was calculated as $\nu = C \times t$, where C is the viscometer's constant and t is the efflux time. Dynamic viscosity (η) was then calculated to be $\eta = \nu \times \rho$, where ρ is the density of the water at measurement temperature. The measurements were taken in triplicate.

Color

The color of the orange drink samples was determined using a Minolta colorimeter to measure *L**, *a**, and *b**. The *L** value corresponds to the degree of lightness, as described by Ali *et al.* [5].

Estimation of the bioactive profile of orange drink

Total phenolic content

The TPC of the orange drink extract was determined using the Folin-Ciocalteu reagent method, as described by Salah-Eldin *et al.* [18].

Vitamin C

The vitamin C content in orange drink samples was measured by titration with 2,6-dichlorophenolindophenol (DCPIP), as described by Salah-Eldin *et al.* [18].

Radical-Scavenging Activity

The efficacy of the prior orange drink extract solution in radical scavenging was assessed using DPPH, following the study by Ali *et al.* [5]. The inhibition % was calculated using equation 1 [19]:

$$\%DPPH\ inhibition = \{(A_{control} - A_{sample}) / A_{control}\} \times 100 \quad (1)$$

Microbiological evaluation

The mould and yeast count was estimated in orange drink samples prepared using MW, compared with samples treated with heat via pasteurization (OD1) and C, with the conventional orange drink serving as a control. One milliliter was withdrawn from each sample without dilution. Potato dextrose agar medium was used to estimate molds and yeasts, which were then incubated in an Astell Hearson incubator at 28 ± 2 °C for 5 days.

Sensory evaluation

The sensory attributes of orange drink, including taste, color, odor, aftertaste, and overall acceptability, were measured using a nine-point hedonic scale to identify the most suitable preservation method for preparing orange juice with acceptable quality characteristics for consumers, as described by Arilla *et al.* [20]. A semi-trained panel of 30 members (20 females and 10 males, aged 25-45 years) conducted this evaluation. The panelists were asked to rate the samples based on their quality characteristics using the following scale: 0-2 indicated strong disapproval, 3-4 indicated mild disapproval, 5 indicated neutral, 6-8 indicated moderate approval, and 9 indicated excellent. Samples were randomly distributed within each experimental block, assigned codes, and presented to the panelists in a sensory evaluation lab. After tasting each sample, water was provided to each participant to cleanse their palate.

Estimation of shelf-life

Shelf life was defined as the initial time at which either (a) the ascorbic acid level fell to less than 50% of its initial value (t_{50}); (a) the standard nutritional limit used in shelf-life studies on labile vitamins or (b) the mold & yeast concentration reached more than 3 log CFU/mL (≈10^3 CFU/mL) an extensively cited acceptability/safety threshold for fruit juices. The loss of ascorbic acid was characterized by first-order kinetics; when a good k value was known, the t_{50} was calculated from the half-life fitted ($t_1/_2 = \ln 2 / k$). When the data obtained fell at or above the 50% point, linear interpolation between adjacent sampling days was used to determine the calendar day at which 50% was reached. Microbial exceedance times were linearly interpolated from linear interpolation between sampling points on either side of the 3-log CFU/mL threshold. These conditions are consistent with previous kinetic and microbiological approaches to the shelf-life of citrus juice [21, 22].

Statistical analysis

Statistical analysis was carried out using CoStat software (Version 6.45, CoHort Software, Monterey, CA, USA). Results are expressed as mean ± standard deviation of three independent replicates (n = 3). One-way analysis of variance was used to compare results among groups, and Duncan's multiple-range test was used for post hoc analysis at the $p < 0.05$ significance level. Some figures were created using Python (version 3.11) and the Matplotlib library.

RESULTS AND DISCUSSION

Physicochemical properties of magnetized water

There is no significant difference between the pH values of tap water (7.35) and magnetized water (7.32), indicating that treating water with a magnetic field does not alter its acid-base balance. Our results are consistent with earlier studies, which suggest that magnetic treatment typically does not significantly alter water pH, especially when the initial pH falls within the neutral range [23]. Maintaining pH stability is essential, as it ensures that MW remains acceptable and safe for consumption and does not negatively affect its buffering capacity. Although Wang *et al.* [9] reported that minor changes may occur depending on the intensity and exposure time of the magnetic field, their findings confirm that magnetic treatment preserves water's natural neutrality, particularly its microbial stability, which is vital for its suitability for both domestic and industrial applications [13].

The results of magnetic water treatment show that magnetized water had higher TDS (136.67 ppm) and EC (263 μS/cm) than tap water (117.33 ppm and 230.67 μS/cm, respectively). This increase indicates that the magnetic treatment may enhance the solubility of minerals and promote ionization of dissolved salts. These results are consistent with [11, 12], which reported similar findings, indicating that magnetization can increase ionic mobility and dissolution capacity in water, thereby elevating EC and TDS values. The higher conductivity observed in MW is attributed to a greater concentration of free ions, which may enhance its reactivity and affect chemical or biological processes in food or agricultural applications. These changes could be beneficial in specific vital processes, such as enhancing nutrient absorption in plants; however, further investigation is required to assess their long-term implications [24].

The flow-time experiment revealed that MW had a viscosity of 0.870 mPa·s, slightly lower than that of tap water (0.890 mPa·s), indicating a reduction of approximately 2.3%. This decrease in viscosity indicates that treating water with a magnetic field may alter its hydrogen-bonding network, potentially reducing intermolecular resistance to flow. Similar trends have been documented by Pang & Deng [25], who reported that magnetization decreases viscosity by reorienting water dipoles and disrupting larger water clusters. Although the alteration is relatively small, such physicochemical changes could significantly affect water transport characteristics in both industrial and biological applications, whether this influence is time-stable remains debated in the literature and warrants further investigation.

Physicochemical evaluation of orange drink

pH

At time zero, all the drink samples had pH values quite similar to each other (around 3.3-3.4, as shown in Figure 1), consistent with the intrinsic acidity of citrus. Throughout storage, however, all treatments showed a general decline in pH, with the most significant change observed in the control (C). Acidification is mainly driven by microbial growth and the consequent production of organic acids (acetic, citric, and lactic) as metabolic by-products by spoilage microorganisms [26]. Sodium benzoate-treated samples (OD2) had significantly higher pH values than the control throughout storage. This preservative function in acid beverages occurs when benzoic acid penetrates microbial cells, disrupting intracellular enzymatic processes, inhibiting growth, and reducing acid production [27]. Previous studies of fruit juices had shown that OD2 retarded microbial growth and extended the shelf life of beverages without significantly changing sensory attributes [28]. This suggests the relatively stable pH of the OD2 samples, particularly after 9-15 days.

Pasteurization (OD1) also delayed the rate of pH decline compared with the control, although its effect was weaker than that of OD2. This is attributed to heat-induced inactivation of vegetative microbial cells and to partial enzyme denaturation, which initially restricted acid generation. The presence of heat-resistant spores and residual enzymatic activity may account for the observation that pasteurized samples still showed a measurable decline in pH during storage [29].

Magnetic field (MF) treatment yielded results parallel to those of the OD1 and OD2 treatments, suggesting that non-heat preservation methods can effectively stabilize juice pH. The exact mechanism of microbial inactivation through magnetic fields remains unclear. Yet, proposed hypotheses encompass change in cell membrane permeability, disruption of enzyme systems, and interference with ionic transport, which can limit microbial growth and acidification [30]. Interestingly, magnetic treatment avoids the adverse sensory and nutritional impacts that can sometimes be transferred by heat treatments, representing a clean-label preservation solution of immense potential.

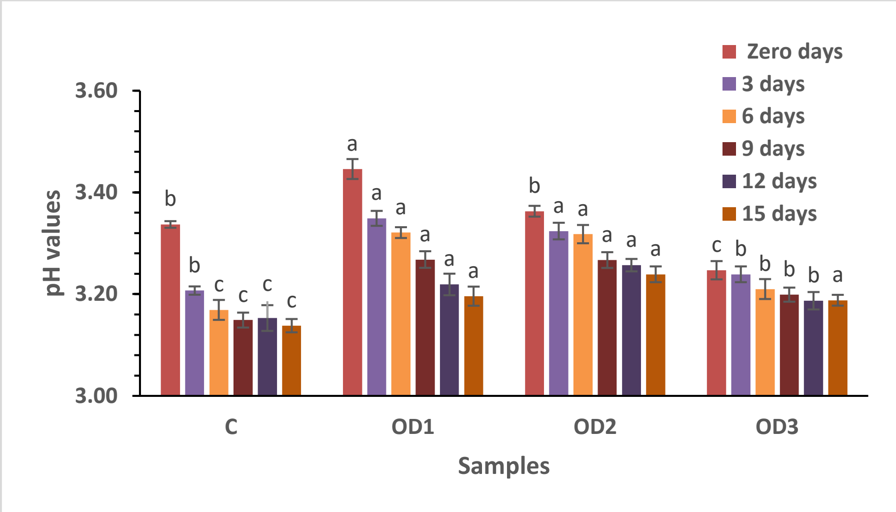


Figure 1. Changes in pH values of orange drink samples during refrigerated storage for 15 days. Where, C: orange drink without any treatments; OD1: orange drink treated with pasteurization at 90°C for 60 seconds. OD2: orange drink contains 0.1% sodium benzoate; OD3: orange drink prepared using magnetic water. Values represent means ± standard deviation (n = 3). Different letters above the bars within the same storage day indicate significant differences ($p \leq 0.05$) among treatments, as determined by Duncan's Multiple Range Test (DMRT).

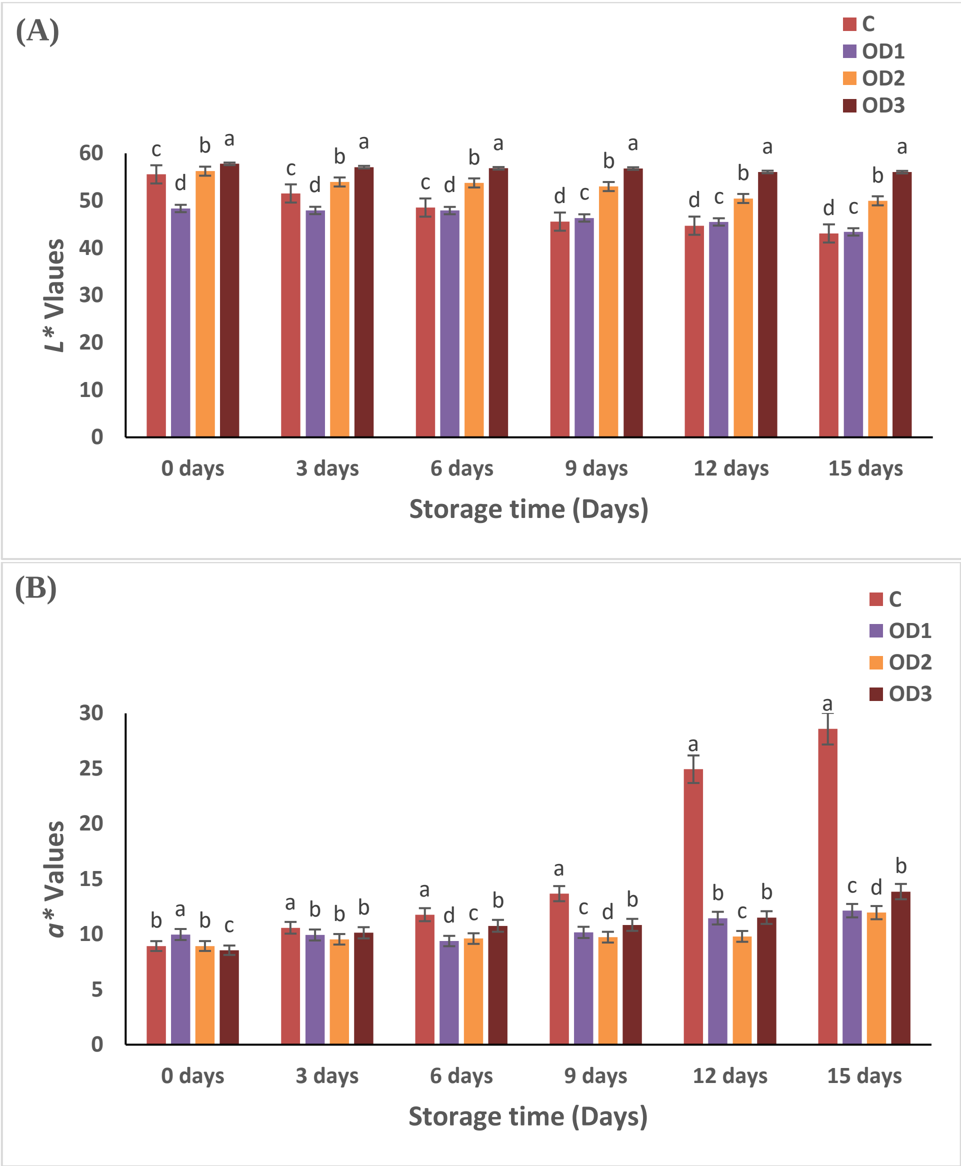
In contrast, sodium benzoate showed the best performance in maintaining a stable pH, followed by pasteurization and magnetic field treatment, whereas the control showed the greatest pH decline. These results indicate that while chemical preservatives remain the most effective for shelf extension, magnetic treatment shows promise as a non-thermal method for maintaining juice quality. These findings align with emerging research favoring new preservation technologies that balance microbial safety, shelf stability, and consumers' desire for minimally processed foods [28, 30].

Color

The control drink (C) showed a gradual increase in *a** values during storage (8.93 to 28.61), attributed to the oxidation of vitamin C and polyphenols, resulting in the formation of brown/red polymeric pigments [31]. Pasteurization (OD1) initially increased redness due to pigment breakdown and heat-induced browning intermediates [33]. Subsequent increases in storage (8.98 to 17.14) were due to the accumulation of oxidation and polymerization products derived from vitamin C and phenolic compounds [31]. Sodium benzoate (OD2) halted this increase *(a*)* in both control and pasteurized samples (7.93 to 10.96), reflecting its ability to suppress oxidative conversions to some extent. Interestingly, magnetized water-treated drink exhibited the smallest increase in *a** values (9.55 to 16.86) during storage, indicating greater stability of natural pigments and lower enzymatic browning than all other treatments [10].

The control juice showed a declining trend in *b** upon storage (51.02 to 35.76), reflecting the sensitivity of carotenoids to oxidation [35]. Pasteurization resulted in a significant decline in *b** (from 45.13 to 30.10), which is consistent with the thermal breakdown of carotenoid pigments, particularly β-carotene and xanthophylls [36].

This trend persisted during storage due to oxidation of carotenoids and the presence of trace enzymatic activity. Whereas Sodium benzoate slowed but did not prevent this decline (49.51 to 42.88), it provided some protection against yellowness. Magnetized water-treated orange drink, however, showed the greatest retention of *b** values (49.79 to 42.43), indicating that carotenoid stability was enhanced under magnetic treatment, possibly through reduced oxidative stress and pigment protection [9].



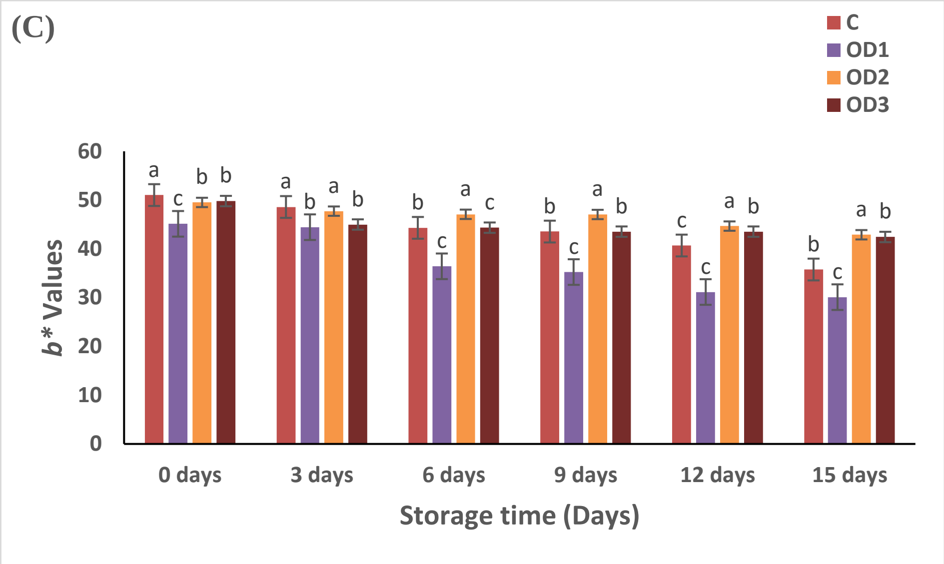


Figure 2. Effect of preservation method on color parameters (A: L^*, B: a^*, C: b^*) of orange juice during refrigerated storage for 15 days.

Total soluble solids

The initial TSS values of around 16% were the same in all orange drink samples. The latter differences, however, depended on the treatment applied during cold storage (Figure 3). The control juice (C) experienced the most dramatic decline, reaching 13.5% by day 15. This drastic fall is caused by microbial growth and metabolic activities, as sugars ferment and are converted into organic acids and ethanol, thereby decreasing the soluble solids content [37, 38].

On the other hand, the pasteurized drink (OD1) was more stable, and TSS decreased more slowly to ~14.7% after 15 days. Pasteurization can effectively inactivate the majority of the spoilage microorganisms. Still, residual enzyme activity (e.g., invertase, pectinases) and slow non-enzymatic reactions, such as Maillard browning and ascorbic acid breakdown, can continue to lead to the gradual loss of soluble solids during storage [22, 39].

Most notably, the sodium benzoate (OD2) and magnetized water (OD3) treatments performed the best, with TSS values remaining at 14.4% and 14.3%, respectively, on day 15. The two treatments were not statistically different from one another, indicating that both preservation treatments effectively prevented TSS from decreasing. Sodium benzoate has also been shown to inhibit microbial growth by inhibiting enzymatic activities and intracellular acidification, thereby slowing sugar metabolism [27]. Concurrently, magnetized water treatment has also been shown to exhibit antimicrobial effects by altering cell membrane permeability and ionic balance, as well as stabilizing solute molecules, which may account for its effectiveness in maintaining TSS levels [27].

Overall, the findings show that although all treatments showed the same reduction in TSS during cold storage, sodium benzoate and magnetized water performed best at maintaining soluble solids, beating the control and pasteurized juice. This highlights that treatments can efficiently suppress microbial fermentation and enzymatic hydrolysis, thereby improving the physicochemical stability of orange drinks during cold storage.

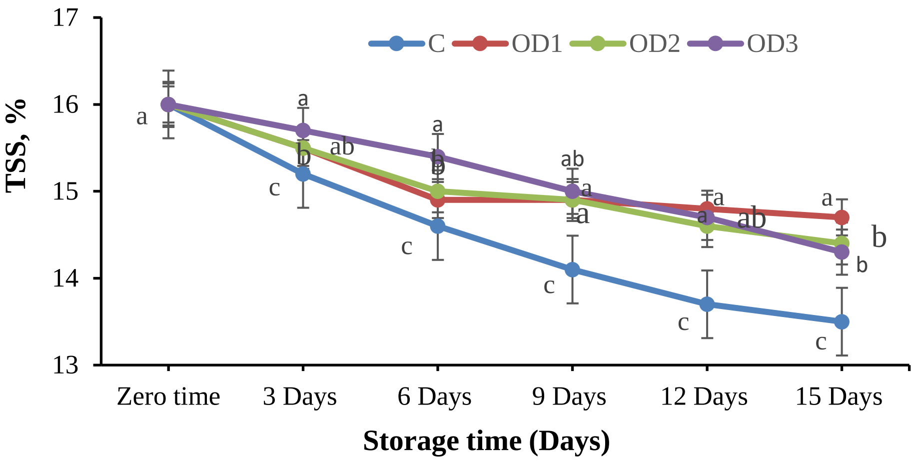


Figure 3. Changes in TSS, % of orange drink samples during refrigerated storage for 15 days.

Bioactive profile of orange drink

Vitamin C content

The ascorbic acid (vitamin C) content of orange drink samples showed significant differences during refrigerated storage, with notable differences between treatments (Figure 4). The control sample (C) showed the most critical loss, from 820.5 mg/100 mL on day 0 to 398 mg/100 mL on day 15, representing a 51.5% reduction. This loss may be attributed to oxidative degradation and enzymic activity, since ascorbic acid is sensitive to oxygen, light, and trace enzymic activity during storage [40, 41]. The sharp decline in control emphasizes the need for preservation activities to allow nutritional integrity.

Pasteurized samples (OD1) also showed fairly consistent vitamin C levels, ranging from 525 mg/100 mL on day 0 to 499 mg/100 mL on day 15, corresponding to only a 5.0% reduction. This implies that although heat treatment can destroy some of the heat-labile vitamin C, it will also inactivate oxidizing enzymes such as ascorbate oxidase and peroxidase, thereby retarding subsequent breakdown during storage [22, 34]. The slight changes detected here confirm that pasteurization can help preserve ascorbic acid stability during short-term cold storage.

OD2-treated samples contained more vitamin C than the pasteurized and control juices, ranging from 825 mg/100 mL on day 0 to 598 mg/100 mL on day 15, corresponding to a 27.5% reduction. The preservative effect of sodium benzoate may have inhibited microbial activity and oxidative reactions, thereby improving the retention of ascorbic acid [42]. These findings are consistent with previous research that benzoates might protect labile nutrients from degradation during storage.

Interestingly, treatment with magnetized water (OD3) also exerted a protective effect, with a gradual decline in vitamin C from 792 mg/100 mL at day 0 to 587 mg/100 mL at day 15, corresponding to a 26.3% reduction. Such retention is consistent with sodium benzoate, suggesting that magnetized water might alter the redox environment or reduce the catalytic activity of dissolved oxygen, thereby interfering with oxidative deterioration [27]. While the mechanisms underlying them remain to be elucidated, these results suggest that magnetized water may be a viable non-chemical preservation method.

In general, the order of vitamin C stability among treatments was OD2 > OD3 > OD1 > C, indicating that chemical (sodium benzoate) and physical (magnetized water, pasteurization) preservation treatments significantly improved nutrient retention compared to the control. The findings justify the inclusion of such treatments in orange-based beverages to preserve their nutritional and functional property during storage.

Total phenolic content

The TPC in orange drink samples fluctuated moderately during refrigerated storage, with significant differences between treatments (Figure 4). The control sample (C) showed the maximum decline, decreasing from 9490.7 mg GAE/L on day 0 to 5078.7 mg GAE/L on day 15, representing a 46.5% loss. This severe loss is attributed to the sensitivity of phenolic compounds to oxidative degradation, enzymatic action by polyphenol oxidase, and oxygen interactions during storage [34, 40, 43]. The sharp decline in control indicates the urgency for applying preservation practices to maintain bioactive compounds and nutritional integrity.

Pasteurized samples (OD1) were very stable, with TPC decreasing by only 5.3% from 5612 mg GAE/L on day 0 to 5316 mg GAE/L on day 15. This means that heat treatment not only degrades some phenolics but also disables oxidative enzymes that catalyze their degradation during cold storage [22, 32]. These findings support the conclusion that, despite its limitations, pasteurization is highly effective at maintaining phenolic stability in orange beverages.

Samples treated with sodium benzoate (OD2) also showed improved TPC retention compared to the control, from 8149.3 mg GAE/L at day 0 to 6358.7 mg GAE/L at day 15, which corresponded to a 22.0% reduction. The preservative effect of sodium benzoate may have suppressed microbial metabolism and reduced oxidative processes, leading to phenolic loss and thereby improving phenolic stability [43]. This finding signifies the efficacy of sodium benzoate in preserving phenolic compounds under refrigerated storage.

Interestingly, magnetized water (OD3) treatment also showed a protective effect against TPC, with levels decreasing progressively from 8230.7 mg GAE/L at day 0 to 7126.7 mg GAE/L at day 15, representing a 13.4% reduction. This preservation is comparable to that of sodium benzoate, suggesting that magnetized water may slow oxidative spoilage by altering the redox balance or decreasing the reactivity of dissolved oxygen in the juice. Although the mechanisms remain unclear, these findings suggest that magnetized water may be an effective non-chemical preservation method for enhancing phenolic stability in fruit drinks. In the absence of direct redox measurements, the preservation of antioxidant compounds indicates that magnetized water treatment can improve oxidative stability during refrigerated storage.

Antioxidant activity

Antioxidant activity of orange drink samples exhibited clear discrimination among treatments during refrigerated storage (Figure 4). The control sample (C) initially showed a high antioxidant activity of 73.49%, which decreased progressively to 30.03% by day 15. This severe loss can be attributed to oxidative degradation of ascorbic acid, phenolic compounds, and other bioactive antioxidants, which are very sensitive to oxygen, light, and enzymatic activity during storage [40]. The precipitous drop in antioxidant capacity in the control underscores the untreated samples' vulnerability to oxidative spoilage.

Pasteurized samples (OD1) consistently showed low antioxidant activity, ranging from 19.97% on day 0 to 15.50% on day 15. The low initial readings are likely due to heat-induced degradation of thermally labile antioxidants, such as vitamin C and phenolics, during pasteurization [22, 34]. However, the low loss over storage suggests that enzyme inactivation via heat treatment stabilized the remaining antioxidant activity.

Sodium benzoate (OD2) treated samples demonstrated significantly higher antioxidant capacity than the control and pasteurized samples, with 73.35% at day 0 and 58.82% at day 15. The preservative effect of sodium benzoate may have suppressed microbial growth and oxidative reactions, preventing the loss of phenolic compounds and other antioxidants during storage. This finding aligns with earlier studies that confirm that benzoates can stabilize bioactive molecules in fruit beverages [42].

OD3 treatment also provided protection, and antioxidant activity was initially noted at 70.49% and sustained at 62.80% on day 15. Although some reduction was observed, MF-treated samples exhibited greater antioxidant activity than pasteurized juice and were comparable to sodium benzoate. This suggests that magnetized water may have maintained the redox stability of the juice, either by altering dissolved oxygen activity or by enhancing free radical scavenging.

Microbiological evaluation of orange drink

Yeast and mould counts in orange drink samples showed significant differences among treatments during cold storage (Table 1). The control sample (C) exhibited a slow rise in fungal load from 1.45 Log CFU mL^{-1} on day 0 to 6.87 Log CFU mL^{-1} on day 15. This concentration far exceeds the commonly accepted safety limit of ~3 Log CFU/mL for yeast and mould in fruit juices, indicating rapid spoilage [21, 44]. Similarly, studies reveal that typical initial yeast/mould cultures in brand-new packages of orange juice are about 1.8×10^3 CFU/mL (~3 Log), which may increase to >6 Log CFU/mL following 15 days of cold storage, confirming the spoilage of your control samples [28]. The slow rise suggests the absence of sufficient preservation processes since natural microflora developed, even with cold storage, which has been demonstrated to slow but not inhibit microbial growth [45]. Such bacterial growth not only raises safety concerns but can also lead to spoilage due to enzymatic activity and metabolic by-products.

In contrast, pasteurized samples (OD1) never showed detectable yeast or mould throughout the storage period. The absence of growth demonstrates the effectiveness of heat treatment in eliminating fungal spores and vegetative cells, thereby providing microbiological stability and extending the safety of refrigerated juice [21, 45]. This, however, occurs at a cost in the form of potential heat-mediated changes to nutritional and sensory quality, as previously reported.

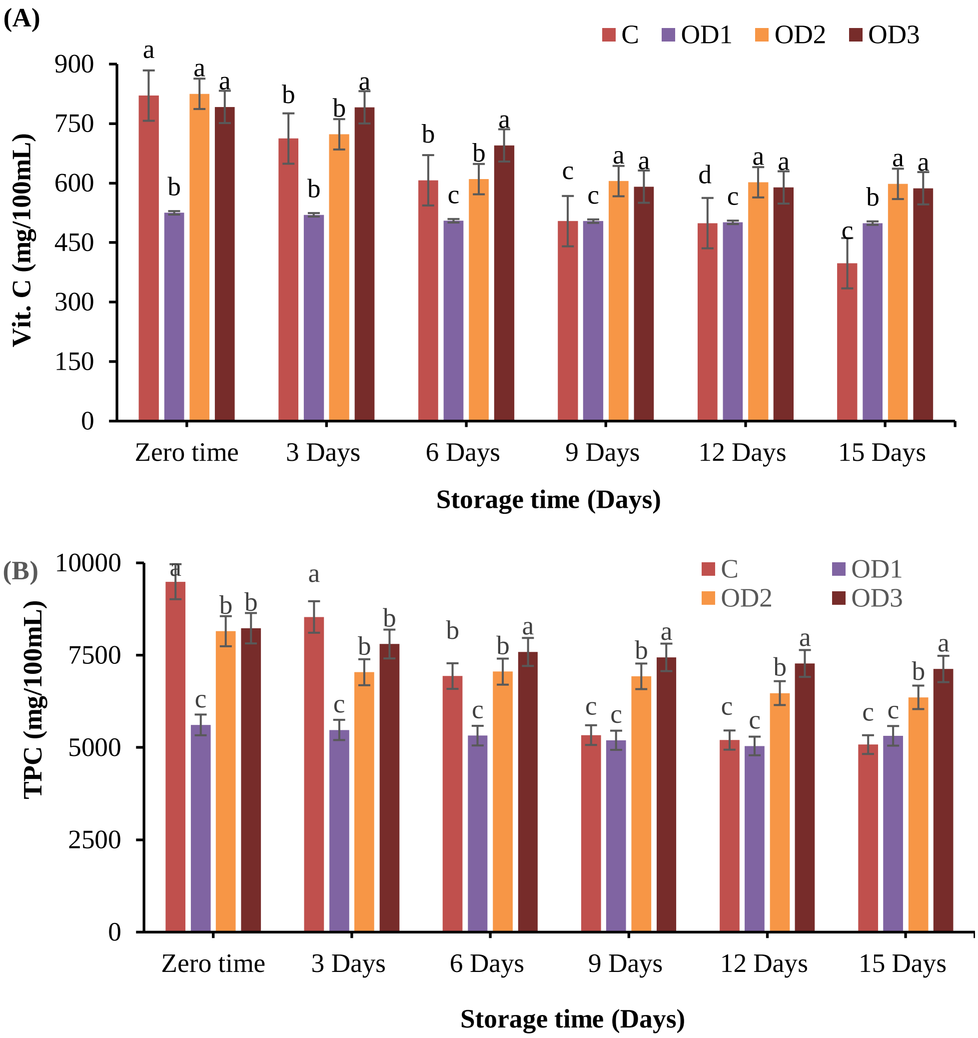
OD2-treated samples demonstrated adequate antifungal protection, with initial counts not detected and a minimal increase to 2.41 Log CFU mL^{-1} on day 15, which is far below the unacceptable limit. This is due to the preservative preventing the growth of yeast and mould by interfering with microbial metabolic processes, particularly in acidic environments typical of fruit drinks [46]. The slight increase observed towards the end of storage suggests that, while OD2 is effective, its preservative action can be lost over time.

Simultaneously, magnetized water (OD3) treatment inhibited fungal growth, with no detectable counts until day 9, followed by low counts (1.11 Log CFU mL^{-1}) before rising slightly to 1.20 Log CFU mL^{-1} on day 15; these values remain well below the spoilage threshold. Although the exact mechanism remains unclear, studies suggest that magnetized water may alter the microbial cell membrane or reduce oxygen solubility, thereby creating unfavorable conditions for fungal growth [47]. Moreover, the increase in electrical conductivity and dissolved solids might suggest increased ion mobility and the dissolution of minerals in the aqueous phase. These physicochemical changes might affect microbial metabolism by altering osmotic balance and ion availability in the medium. In acidic drinks such as orange drink, where microbial growth is already limited by the low pH, any alterations in the aqueous phase might have contributed to the reduced microbial growth rate during refrigerated storage. Similar findings have been observed in studies investigating the effect of a magnetic field on the physicochemical properties of water and aqueous systems [13]. These findings indicate that magnetized water can play a supporting role as a part of a multi-hurdle approach to food preservation, but not on its own.

Generally, these results indicate that the control samples, when left untreated, are highly susceptible to fungal spoilage, whereas pasteurization provides complete inhibition. Sodium benzoate and magnetized water treatments provided excellent microbial suppression, with OD3 slightly superior in the long term, making them good candidates for non-thermal preservation of orange-flavored beverages.

Table 1. Effect of processing treatments on mould and yeast count (Log CFU/mL) of orange drink.

Storage time	C	OD1	OD2	OD3
Zero time	1.45 ± 0.55	ND	ND	ND
3 days	2.32 ± 0.47	ND	ND	ND
6 days	3.18 ± 1.00	ND	1.87 ± 0.83	ND
9 days	4.11 ± 1.03	ND	2.00 ± 1.53	ND
12 days	5.23 ± 0.93	ND	2.12 ± 1.43	1.11 ± 0.77
15 days	6.87 ± 0.88	ND	2.41 ± 1.62	1.20 ± 0.98



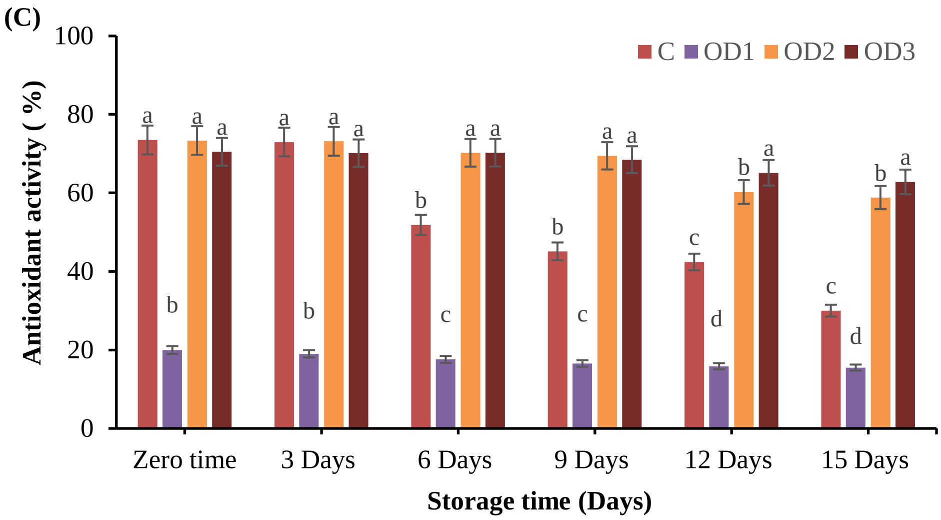


Figure 4. Changes in vitamin C, TPC (mg/100mL) contents (A and B), and antioxidant activity, % (C) of orange drink samples during refrigerated storage for 15 days.

Shelf-life estimation

Using a dual-criterion approach (vitamin C retention to 50% and mold/yeast safety limit of 3 log CFU/mL) (Table 2 and Figure 5), the control orange drink reached the microbiological safety limit first: mold and yeast counts rose from 2.32 log CFU/mL at day 3 to 3.18 log CFU/mL at day 6, and linear interpolation places the 3 log threshold at ≈ 5.4 days; thus the control's shelf life is constrained to approximately 5.4 days by microbiological spoilage. Although vitamin C in the control reached 50% of its initial concentration only near ~14.6 days, this nutritional criterion is not the limiting factor for the unpreserved product. By contrast, pasteurized (OD1), sodium benzoate (OD2), and magnetized water (OD3) treatments remained microbiologically acceptable through 15 days and retained more than 50% of the initial vitamin C during this period. Pasteurized juice exhibited extremely slow ascorbate loss (modeled $t_1/_2$ ≈ 198 days), indicating exceptional short-term nutritional stability. SB and MF also substantially slowed ascorbate degradation (modeled $t_1/_2$ ≈ 33.6 and 28.6 days, respectively), implying t50 values well beyond the 15-day test period. Therefore, for OD1, OD2, and OD3, the earliest criterion was not reached within the study period; their shelf lives are ≥ 15 days under the tested refrigerated conditions.

The dominance of microbial spoilage in determining the control sample's shelf life is consistent with numerous reports that unpreserved fresh juices rapidly support yeast and mold growth even at refrigeration temperatures [21], and that microbiological limits (3 log CFU/mL) are often exceeded within days in unprocessed juices. Pasteurization's effectiveness in suppressing fungal growth and stabilizing vitamin C during short-term storage is likewise well documented. Thermal inactivation of oxidative enzymes and spoilage microflora limits storage-phase ascorbate loss, despite some heat-associated initial losses [33, 36]. The comparable performance of OD2 and OD3 in this study, preserving vitamin C and maintaining yeast/mold counts below regulatory thresholds for at least 15 days, aligns with literature showing that chemical preservatives retard microbial-driven oxidation and that specific magnetic treatments can reduce microbial proliferation and alter redox/oxygen behavior in aqueous matrices [45]. Practically, this means that while unpreserved orange drink would be expected to become microbiologically unacceptable within about a week under refrigeration, treated beverages (OD1, OD2, OD3) demonstrate shelf life of at least two weeks under the conditions tested; longer-term shelf-life projections for OD2 and OD3 (e.g., the ~21-day extrapolated microbial breach for OD2) require confirmatory microbiological monitoring beyond 15 days.

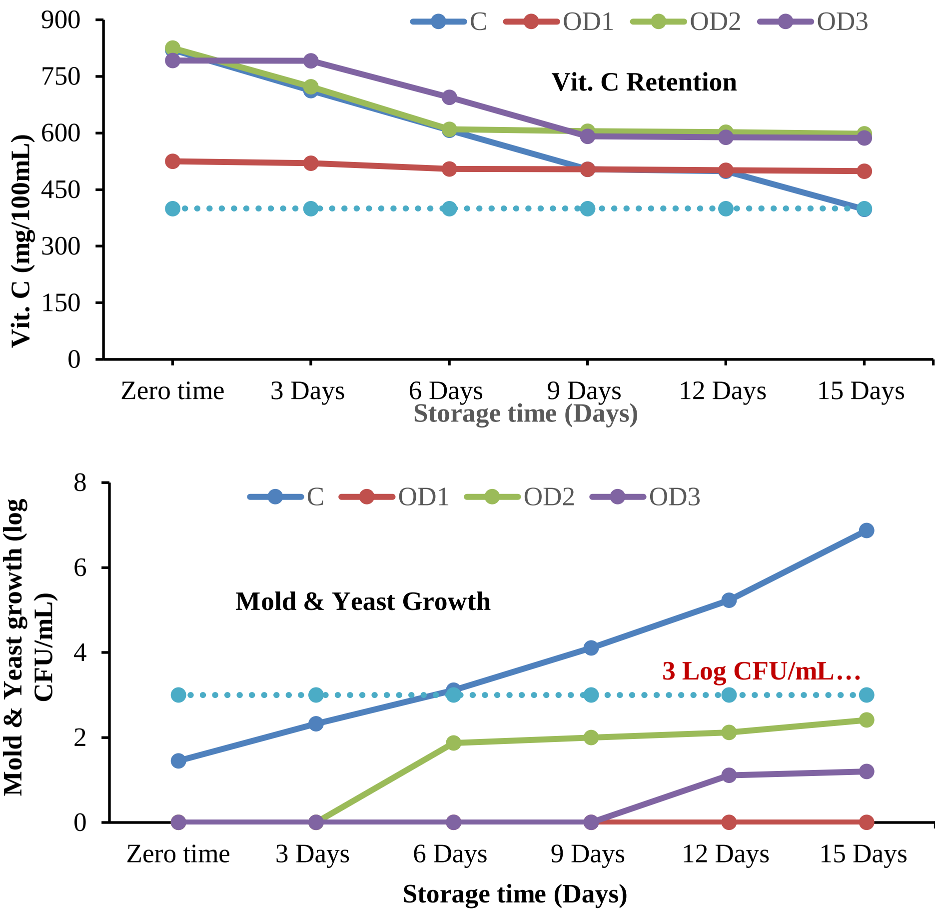


Figure 5. Vitamin C concentration versus storage time, with dashed lines indicating 50% (400 mg/100 mL) of the initial vitamin C concentration; mold and yeast counts versus storage time, with a dashed line at 3 log CFU/mL.

Table 2. Estimated shelf life (days) of orange drink by treatment, based on vitamin C (50% of initial) and mold and yeast (3 log CFU/mL) criteria in refrigerated storage.

Treatment	Vitamin C 50% threshold (t_{50}, days)	Microbial limit (3 log CFU/mL) / estimated exceedance day	Shelf life (days)
C	~14.6 days	~5.4 days (mold/yeast exceeded between day 3 & 6; est. 5.37 d)	≈ 5.4 days
OD1	>>15 days ($t_{1/2}$ fitted ≈198 d → t_{50} ≈198 d)	ND through 15 d	≥ 15 days
OD2	>15 days ($t_{1/2}$ fitted ≈33.6 d → t_{50} ≈33.6 d)	Not exceeded by day 15 (value = 2.41 at d15); linear extrapolation suggests ~21 d to reach 3 log	≥ 15 days

Treatment	Vitamin C 50% threshold (t_{50}, days)	Microbial limit (3 log CFU/mL) / estimated exceedance day	Shelf life (days)
OD3	>15 days ($t_{1/2}$ fitted ≈28.6 d → t_{50} ≈28.6 d)	Not exceeded by day 15 (value = 1.20 at d15); trend indicates much later exceedance	≥ 15 days

ND: not detected.

Sensory evaluation

The sensory evaluation of the orange drink at time 0 revealed significant differences among treatments in taste, odor, and overall acceptance. In contrast, color scores were relatively consistent for samples (Table 3). Control sample (C) and magnetized water treatment (OD3) achieved the highest panel scores (9.00 ± 0.53 and 9.00 ± 0.14, respectively) and excellent general acceptability (8.71 ± 1.00 for C and 8.83 ± 1.28 for OD3). Both treatments also tasted more superiorly (8.82 ± 0.72 and 8.90 ± 1.10, respectively). They smelled more superiorly (9.00 ± 1.14 and 9.00 ± 0.96), indicating that magnetized water treatment did not compromise the drink's sensory quality, which was equivalent to that of the untreated control. Those high scores suggest strong panel agreement, with most panel members scoring 8-9, reflecting high product acceptability.

Conversely, pasteurization (OD1) and sodium benzoate (OD2) treatments registered lower taste and odor scores (7.42 ± 1.31 and 7.45 ± 1.22 for taste; 8.10 ± 1.20 and 8.02 ± 0.67 for odor, respectively), which reduced their overall acceptance (7.96 ± 1.08 and 7.72 ± 0.93, respectively). This reduction may be attributed to heat-induced changes in volatile aroma compounds and flavor-active molecules in pasteurized citrus juice [41, 49] and to the residual chemical aftertaste associated with benzoate preservatives [48], respectively. Studies on orange and citrus fruit juices confirm that chemical preservatives and heat treatment can alter taste perception, reducing freshness and volatile retention, even though color is not changed [50].

As might be expected, magnetized water treatment preserved sensory characteristics at levels statistically comparable to those of the control. This is consistent with recent evidence that non-thermal preservation techniques, such as magnetic field treatment or pulsed electric fields, are superior to standard heat treatments in maintaining the fresh-like sensory nature of fruit juices [22]. These reports highlight the merits of magnetized water as a viable alternative technique for extending shelf life without compromising consumer acceptability.

Table 3. Impact of the addition of sodium benzoate, magnetic water treatments, and pasteurization on the sensory properties of orange drink at zero time.

Treatments	Color	Taste	Odor	Overall acceptance
C	9.00^{a} ± 0.53	8.82^{a} ± 0.72	9.00^{a} ± 1.14	8.71^{a} ± 1.00
OD1	8.00^{a} ± 1.02	7.42^{b} ± 1.31	8.10^{b} ± 1.20	7.96^{b} ± 1.08
OD2	9.00^{a} ± 0.56	7.45^{b} ± 1.22	8.02^{b} ± 0.67	7.72^{b} ± 0.93
OD3	9.00^{a} ± 0.14	8.90^{a} ± 1.10	9.00^{a} ± 0.96	8.83^{a} ± 1.28

CONCLUSION

A comparative evaluation of preservation methods revealed that the technique significantly affected the physicochemical, bioactive, microbiological, and sensorial quality of the orange drink when refrigerated. Physicochemical attributes, including pH and TSS, remained relatively stable during sodium benzoate, pasteurization, and magnetized water treatments. In contrast, the control exhibited a significant decline in these parameters. For bioactive compounds, total phenolic content and vitamin C decreased in a stepwise manner with storage. Still, their retention was much higher in magnetized water and in sodium benzoate-treated samples than in the control. Similarly, antioxidant activity was retained at the highest level in magnetized water and sodium benzoate treatments, whereas the control sample showed a drastic reduction. Microbiological analysis confirmed that mold and yeast growth accelerated rapidly in the control, exceeding reported safety levels, whereas treatments with sodium benzoate, pasteurization, and magnetized water greatly retarded microbial growth during storage. Interestingly, magnetized water showed microbial safety levels comparable to those of chemical preservatives, without synthetic additives. Sensory evaluation indicated that sodium benzoate treatment negatively affected taste and odor acceptability, while pasteurization slightly altered the sensory response due to heat effects. Magnetized water, however, kept sensory attributes such as color, flavor, odor, and overall acceptability at levels very close to those of the control. Combined, these findings suggest that magnetized water is a promising non-thermal, non-chemical preservation technology for fruit juice, capable of maintaining nutritional, microbiological, and sensory quality during short-term cold storage. Its performance was similar to that of sodium benzoate, without the negative aspects associated with chemical preservatives and heat processing. Long-term stability, scalability, and mechanistic insights from follow-up studies should establish the legitimacy of magnetized water as a green preservation strategy in the beverage sector.

Conflict of interests

The authors confirm that there are no conflicts of interest associated with this publication.

Data availability

The data are available upon reasonable request.

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