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RESEARCH

Effect of Microcontroller-Based Pulsed Magnetic Pretreatments on Some Quality of Frozen-Thawed Mango and Tomato

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Abstract

The current study applied a microcontroller pulsed magnetic field (PMF) device to pretreat mango and tomato prior to freezing and storage. The main goal is to investigate the effect of field intensities (9 T, 14 T, and 20 T) and treatment duration (5, 10, and 15 min) on some qualities including vitamin C content, total soluble solids (TSS), pH, drip loss, color change, and firmness of frozen-thawed mango and tomato under short-term frozen storage. The treated and untreated samples were frozen at − 18 °C and stored (at − 18 °C) for 2 weeks. Standards methods were employed to measure the quality parameters of the samples. The results showed that the PMF pretreatment device maintained vitamin C content and TSS of the frozen-thawed samples compared to untreated frozen-thawed ones. The device lowered the drip loss with no meaningful change in the pH. Moreover, photospectometry and texture meter confirmed that the color changes and firmness level of the samples treated at 20 T for 5 min were linked to unbroken cell structure in comparison to the untreated (control) samples. In conclusion, PMF device operated at 20 T and 5 min significantly preserved the vitamin C, TSS, color, and firmness and reduced the drip loss of frozen-thawed mango and tomato, enhancing their preservation.

Keywords Magnetic field · Freezing · Mango · Tomato · Qualities · Preservation

Introduction

Preservation techniques such as cooling (Alabi et al., 2021, 2023a), drying (Alabi et al., 2016; Caparino et al., 2012; Lamidi et al., 2019; Michalska et al., 2018), and freezing (Alabi et al., 2020, 2022; Kaur & Kumar, 2019; Kiani et al., 2011, 2012) have been applied for preserving common fresh fruits and vegetables (FV). Conventional freezing methods are prone to slow cooling rates, leading to the formation of large ice crystals in fruits (Alabi et al., 2020; Li et al., 2018; Mahato et al., 2019). These large crystals damage the cell walls, resulting in structural collapse upon thawing. Lyu et al. (2020) confirmed that slow freezing results in a high degree of cellular damage due to the formation of large ice crystals. This damage led to significant changes in texture, making the tomatoes mushy upon thawing. The researchers used cryo-scanning electron microscopy (cryo-SEM) to observe that air-blast frozen tomatoes had more extensive structural damage than those frozen using rapid freezing methods. Zhang et al. (2021a) investigated the effects of air-blast freezing on mangoes and found that it caused a considerable decline in firmness and an increase in drip loss after thawing. This was due to ice crystal growth during the slow freezing process, which caused the collapse of cell walls and the release of intracellular fluids.

More so, conventional freezing methods often fail to completely deactivate enzymes such as polyphenol oxidase (PPO) in fresh cellular foods. This results in browning and the degradation of vitamins, particularly vitamin C, during storage and thawing (Sun et al., 2022). Sun et al. (2022) demonstrated that traditional air-blast freezing allowed enzymatic activity to persist in tomatoes during storage, leading to significant browning and vitamin C degradation. Tomatoes frozen using this method retained only 60% of their original vitamin C content after 30 days of storage. Zhang et al. (2021b) showed that mangoes subjected to slow freezing (air-blast and contact freezing) had higher levels

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of enzymatic browning due to incomplete enzyme inactivation. Vitamin C degradation was higher in mangoes frozen using slow freezing methods, with a reduction of up to 35% compared to those frozen using rapid methods.

Similarly, one of the biggest drawbacks of conventional freezing methods is the irregular and uneven thawing that occurs. Because the outer layers of the fruit thaw more rapidly than the inner layers, the thawed fruit often suffers from inconsistent textures (Zhao et al., 2021). According to Zhao et al. (2021), the thawing behavior of air-blast frozen tomatoes revealed that irregular thawing caused the outer layer of the fruit to become excessively soft while the inner layer remained partially frozen. This uneven thawing resulted in poor textural quality. Liu et al. (2023) analyzed the effects of conventional freezing and thawing on mangoes. The study found that slow freezing led to uneven thawing, with the external layers becoming over-softened while the internal core remained firm. This inconsistency greatly diminished the fruit's overall quality and appeal.

Conventional freezing methods also lead to significant water loss during thawing, which affects the texture and appearance of tomatoes (Wang et al., 2023). Wang et al. (2023) showed that air-blast frozen tomatoes had 25–30% higher drip loss compared to those frozen with rapid freezing technologies. This loss of water significantly impacted the firmness and overall textural integrity of the tomatoes. Recently, García-López et al. (2022) found that air-blast frozen mangoes exhibited increased drip loss, which correlated with a decline in the fruit's firmness and texture quality. The formation of large ice crystals was identified as the primary cause of the cell wall rupture, leading to excessive water loss during thawing.

Due to its effectiveness in controlling the ice crystals formation, fast freezing is a subject of global study (Alabi et al., 2020; Jariyawaranugoon, 2015; Jha et al., 2017a, 2017b; Kobayashi & Suzuki, 2019; Rodríguez et al., 2019a, 2019b; Tylewicz et al., 2016). Numerous studies have demonstrated that fast freezing produces small crystals and can significantly reduce the quality loss typically associated with conventional freezing methods (Alabi et al., 2022; Parniakov et al., 2016). Emerging technologies, such as magnetic field technology, show promise in reducing ice crystals size during freezing, thereby minimizing cellular damage, enzyme activity, and drip loss (Choi et al., 2015; Dalvi-isfahan et al., 2017; Jha et al., 2017a, 2017b; Kaur & Kumar, 2019; Tang et al., 2020a, 2020b; Zhao et al., 2018). Because of the wave vibration across product masses, electromagnetic field induces magnetic dipole moment with the ability to cause electron spins and creates more hydrogen bonds in cellular foods, promoting freezing process.

Although many findings on the effect of magnetic fields on the freezing characteristics of cellular foods have shown inconsistent results, some authors have reported positive effects (Enzo-Aldoradin et al., 2019; Panayampadan et al., 2022), while some found no effect (Otero et al., 2018) or even negative effects (Kobayashi & Suzuki, 2019). These conflicting findings are major concerns in the food industry. Table 1 summarizes relevant studies on how magnetic fields influence freezing properties of cellular foods.

Several gaps in the application of magnetic fields during freezing have been identified: (1) few authors provided detailed descriptions of the magnetic field techniques used; (2) there was limited investigation into the effect of magnetic fields on different types of food under consistent experimental conditions; (3) few studies explored the synergy between magnetic field process variables (i.e., intensity and duration) and their impact on the quality of frozen-thawed FV, establishing any correlation between them; and (4) research on pulsed magnetic fields (PMF) was relatively scarce, with limited investigation into the effects of varying intensities on the storage characteristics of frozen FV.

In addition, the conflicting results observed during PMF-assisted freezing were mainly attributed to (a) the uncontrolled "Lorentz force" generated by electromotive force on the hydrogen bonds, (b) the migration of magnetically charged particles when a magnetic field is applied on foods, and (c) an insufficient number of replicated experiments. Consequently, there is a need to develop a controlled PMF technology and study its effects on the quality of different cellular foods. A microcontroller-based PMF technology, designed for use as a pretreatment for cellular foods prior to freezing, was developed at Kwara State University (KWASU) and the Federal University of Technology Akure (FUTA) following the procedure outlined by Alabi et al. (2023b). The effect of this microcontroller-based PMF pretreatment on several quality parameters, including vitamin C content, total soluble solids (TSS), pH, drip loss, color, and firmness of frozen-thawed mango and tomato, was investigated after 2 weeks of storage. The potential reasons for varying impacts of PMF on stored mango and tomato were analyzed and discussed. This study aims to provide valuable insights into the effects of microcontroller-based PMF pretreatment on the qualities of frozen-thawed mango and tomato, which could be useful to the food industry.

Materials and Method

Materials used for the microcontroller PMF pretreatment device include galvanized steel plate, copper wire, rectangular plate, triangular electromagnet cores, bolts and nuts, rectifiers, resistors, inductors, voltmeter, and gauss meter. Other materials used for the experiment include mango, tomato, pH meter, brix meter, handheld texture meter, colorimeter, stainless plate, food grade hand gloves, and freezing machine.

Table 1 Relevant findings on the effect of magnetic field on the freezing characteristics of fruits and vegetables

Samples	MFs conditions	Frozen state	Observations	Reference
Mango	OMF at 0, 30%, 50%, and 100% (CAS freezer at − 30 °C)	Freezing point decreased from − 1 to − 5 °C	Freezing through OMF with a CAS freezer causes cell wall breakage, with lesser firmness than the samples frozen using CAS freezer	Enzo-Aldoradin et al. (2019)
Avocado puree	OMF (4 mT, 50 Hz)	Freezing point decreased from − 1.2 to − 6 °C	Samples frozen under the freezing process assisted by a field resulted in a higher pH compared to the control ones	Tan et al. (2019)
Strawberry	Supecooled at 4 °C	Chest freezer at − 85 °C	The frozen strawberries did not exhibit enhanced quality in comparison to the conventional slow freezing because of high water migration and osmotic pressure, causing cell degradation	Kobayashi and Suzuki (2019)
Blueberry	PMF (0–10 mT), and AMF (0–1.74 mT)	Freezing point decreased from	The ideal intensity of PMF at 10 mT enhances the final quality	Tang et al. (2020a)
Cherry	PMF (0–20 mT), and AMF (0–2 mT)	Freezing at − 30 °C and 4 °C/min	PMF of 10 mT decreases nucleation temperature (by 5.59 °C), producing to great supercooling degree and as AMF intensity increases, the corresponding increase in phase change time is undesirable for freezing of fruits	Tang et al. (2020b)
Cucumber	PMF ranging from 0 to 6 mT	Freezing point temperature reduced to 0.74 °C	The application of PMF reduced the initial nucleation temperature and shortened the tempering time for cucumber	Zhang et al., (2021a, 2021b, 2021c)
Freshly cut mango slices	OMF at 10, 50, and 100 mT	Freezing point decreased from − 1.8 to − 5 °C	OMF at 50 mT potentially preserved the original quality and extended the shelf life of freshly cut mango slices	Kang et al. (2021)
Blueberry	PMF-assisted freezing at 36.8 mT/30 Hz, 36.8 mT/60 Hz, 36.8 mT/90 Hz, 36.8 mT/20 Hz, 44.7 mT/30 Hz, 44.7 mT/60 Hz, 44.7 mT/90 Hz, and 44.7 mT/120 Hz	Freezing at − 35 °C	High intensity PMF at 44.7 mT/90 Hz gave enough energy and produced smaller crystals, preserved cellular structure, anthocyanins and polyphenols, and antioxidant capacity among the blueberries when compared with conventional freezing	Arteaga et al. (2022)
Guava	AMF (2.4 mT, 5.6 mT, and 8.8 mT)	− 18 °C for 77 min 35 s	The magnetic field treatment at an intensity of 7.02 mT yielded optimal freezing characteristics for samples with a cube size of 4 cm, as evidenced by a phase change time of 77 min and 35 s, drip loss of 4.97% and firmness of 1.34 N	Panayampadan et al. (2022)

Description of the PMF Pretreatment Device

The microcontroller PMF pretreatment device was developed at Kwara State University (KWASU), located in Malete, Nigeria, at coordinates 51° 27′ 49.144″ N and 19° 13′ 4.303″ E. It mainly consists of a rectangular treatment chamber unit (400 mm × 450 mm × 200 mm) made of aluminum square pipes and a step-down transformer unit. The treatment unit has one covered stationary treatment box (120 mm × 90 mm × 60 mm) made of aluminum for holding the cellular foods. The four electromagnets (two on each side) are properly arranged along the two sides of the treatment chamber, a step-down transformer (from 220 V). Other components include a rectifier, capacitor, copper wire, timer and a microcontroller containing one actuator, two amplifiers, and metal–oxide–semiconductor field-effect transistor (MOSFET). The transformer has tapings for selecting different values of stepped-down voltage (2.42–13.34 V). The plug has a fuse that protects the machine against damage when there is a fluctuation in current. The design and configuration of the machine were done according to Alabi et al. (2023b). Figure 1 indicates set up for experimentation of the microcontroller PMF pretreatment device.

Experimental Procedure

Freshly harvested Ogbomoso mango (*Mangifera indica*) with an average length of 12.93 ± 0.5 mm, average width of 78.85 ± 0.5 mm, and average thickness of 42.14 ± 0.5 mm and plum tomato (*Solanum lycopersicum*) with an average length of 78.25 ± 0.2 mm, average width of 41.15 ± 0.2 mm, and average thickness of 21.35 ± 0.2 mm were purchased from a fresh market at Malete. The samples were cleaned using absorbent paper, sorted, and frozen under PMF-assisted freezing in the laboratory, Department of Food and Agricultural Engineering KWASU. The PMF-assisted freezing was conducted by allowing the samples to pass through the PMF with intensities of 9 T, 14 T, and 20 T, in a treatment chamber at durations of 5, 10, and 15 min. The PMF intensities were produced according to the quantity of turns in the transformer, and were measured using a WTIOB handheld digital Gauss meter. Mango and tomato of weight 100 ± 1 g and 25 ± 1 g, respectively, underwent the subsequent treatments: (1) PMF for 5 min treatment time subsequently freezing at − 18 °C and stored in frozen condition at − 18 °C for 2 weeks; (2) PMF for 10 min treatment time followed by freezing at − 18 °C and stored in frozen condition at − 18 °C for 2 weeks; (3) PMF for 15 min treatment time followed by freezing at − 18 °C and stored in frozen condition at − 18 °C for 2 weeks; and (4) conventional (control) freezing at − 18 °C and stored in frozen condition at − 18 °C for 2 weeks. The PMF freezing experiments were conducted in three replicates. Upon conclusion of the freezing experiments, and storage, the samples were removed from the storage chamber and thawed at 29 °C ambient temperature for 8 h. The qualities of each sample were measured using standard methods. Figure 2 illustrates consecutive phases of the PMF-assisted freezing.

Vitamin C

Samples were processed prior to vitamin C measurement by allowing frozen unknowns to reach ambient temperature of 29 °C to disallow unwanted precipitates. The thawed samples were further subjected to juice extraction in an electric strainer HP Model 850. Vitamin C contents of extracted juice (treated and untreated) were determined (in three replicates) using redox titration method according to Kareem and Ali Hussein (2010) with slight modification. Reagents used include potassium iodide (KI), sulfuric

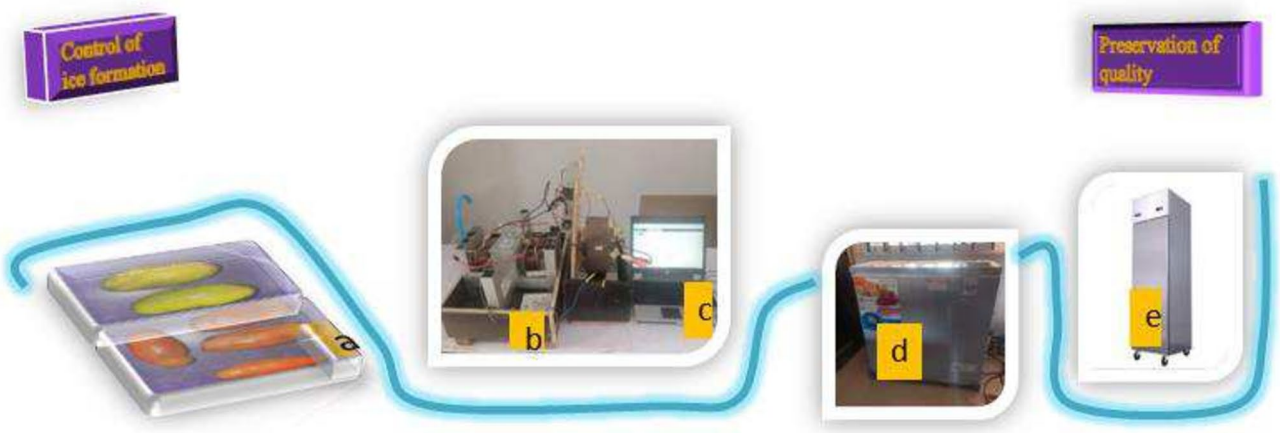


Fig. 1 Set-up for experimentation of the microcontroller PMF-assisted freezing technique: **a** Fresh samples, **b** microcontroller pulsed magnetic field pretreatment device, **c** data acquisition, **d** freezing machine, and **e** frozen storage machine

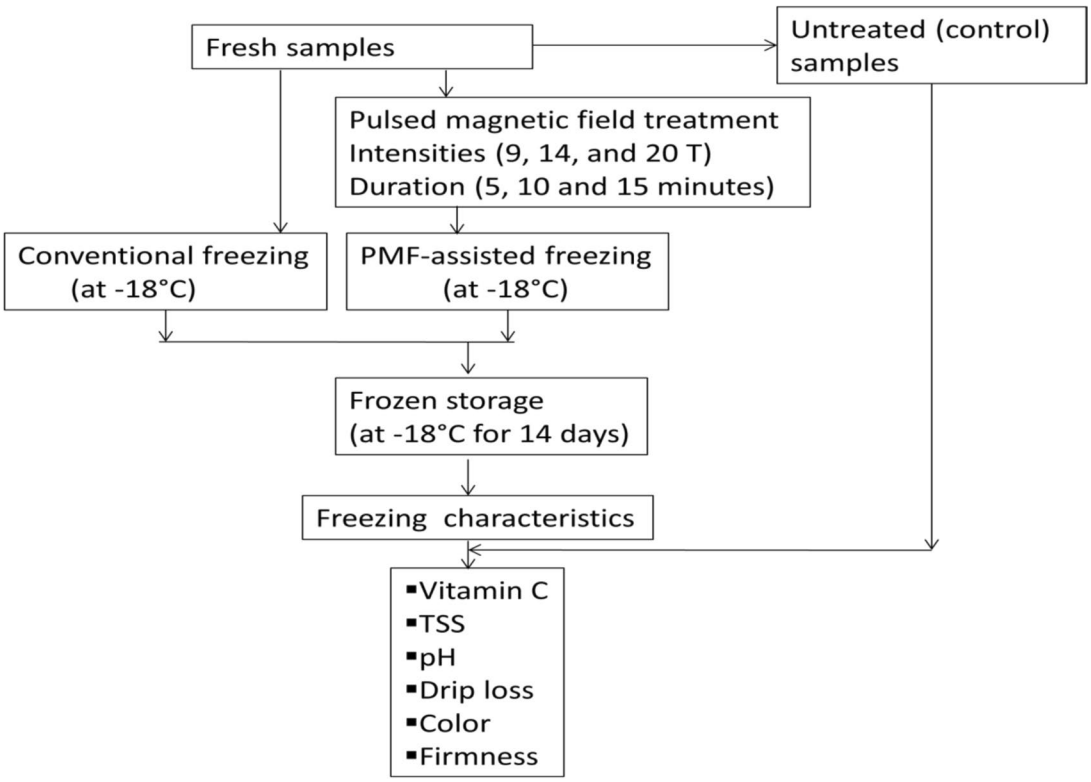


Fig. 2 Consecutive phases of the PMF-assisted freezing

acid (H_2SO_4), potassium iodate (KIO_3), sodium thiosulfate ($Na_2S_2O_3$), and starch. Ten milliliters from each sample was pipetted into a pre-washed conical flask, followed by the addition of 5 ml of 10% potassium iodide (KI) 0.2 M with 1 ml of 0.3 M sulfuric acid (H_2SO_4). Subsequently, a few drops of starch solution were introduced into the flask and titrated against 10 ml of potassium iodate (KlO_3) with a concentration of 0.01 until dark blue color appeared. The amounts of vitamin C content in the samples were evaluated based on the relationship of oxidation reduction reaction of iodate with ascorbic acid as given in Eq. (1):

$$IO^{3-} + 3C_6H_8O_6 \rightarrow 3C_6H_6O_6 + 3H_2O + I^- \quad (1)$$

$$\text{Molar concentration of ascorbic acid in the samples} = \frac{A}{V} \times 1000 \quad (2)$$

$$\text{The mass concentration of ascorbic acid in the samples} = \frac{Mc}{Mm} \quad (3)$$

where A is the amount (mg/100 g) of ascorbic acid in the samples, V is the volume (ml) of ascorbic acid in the samples, Mc is molar concentration (mol/L) of ascorbic acid in the samples, and Mm is molar mass (g/mol) of ascorbic acid in the samples.

Total Soluble Solid (TSS)

The TSS values were measured in three replicates according to Bartz and Brecht (2003). The treated and untreated samples juices were extracted, and a small quantity of the juices was placed on the hand-held refractometer (HRB32-T Kruss Optronic Co., Ltd, Germany) and the total soluble solid values displayed were recorded.

pH

The samples were collected, labeled, and put in a test tube. The pH levels of the samples were gauged with a digital pH meter (pH-3C Hellog, Guangzhou, China) in three replicates according to AOAC (2000) standard method.

Drip Loss

The drip loss values were evaluated in three replicates by the use of the technique outlined by Alabi et al. (2016) as given in Eq. (4):

$$Driploss\% = \frac{W_o - w}{W_o} \times 100 \quad (4)$$

where:

W_o sample weight post freezing

w sample weight post thawing

Color Change

The color change of the mango and tomato samples were evaluated by using a Hunter Lab digital colorimeter (JZ-300 Dongguan Tianjian Machinery Equipment Co., Ltd, Guangdong, China). The conditions observed for color measurements include aperture of 6 mm, D50 illuminant, and 45°/0° annular angle. Three measurements were taken per samples. The results were expressed and recorded as color scales, including light (L*) tone − L* (black), + L* (white)], red (a*) tone [− a* (blue), + a* (red)], and yellow (b*) tone [− b* (green), + b* (yellow)] according to Ali et al. (2016). The color change is expressed as thus:

$$\Delta \boldsymbol{E}^* = \sqrt{[\Delta L^*]^2 + [\Delta a^*]^2 + [\Delta b^*]^2} \quad (5)$$

where:

ΔE^* is the color change

$$\Delta L^* = L_1^* - L_0^*$$

$$\Delta a^* = a_1^* - a_0^*$$

$$\Delta b^* = b_1^* - b_0^*$$

$L_1^* - L_0^*$ is light, $a_1^* - a_0^*$ is red/blue, and $b_1^* - b_0^*$ is yellow/green tones of treated and fresh samples, respectively.

Firmness

The firmness of the fresh and frozen mangoes and tomatoes was examined utilizing the method described by Enzo-Aldoradin et al. (2019) with slight modifications. Firmness determination for each sample was conducted utilizing the compression function in a texture meter (Brookfield, model CT3-1500, USA) equipped with a flat-ended cylindrical plunger having an 8-mm diameter at a rate of 0.5 mms^{-1}. This texturometer provides the maximum firmness (N) corresponding to the penetration depth (mm) in the samples, and thus, the penetration depth was set at 6 mm. Given the slightly convex surfaces near the skin of the samples, layers of approximately 3 mm and 2 mm for mango and tomato, respectively, adjacent to the skins, were removed from each sample before performing the firmness analysis in three replicates. This step was taken to ensure a flat contact between the plunger and the surface of the samples.

Statistical Analysis

All measurements obtained from the experiments were assessed concerning the effect of PMF pretreatment on the quality of frozen-thawed mango and tomato. The PMF intensities and process durations were fixed factors encompassed in the study. The evaluated quality parameters comprised of vitamin C, TSS, pH, drip loss, color, and firmness were regarded as response variables. A two-way analysis of variance (ANOVA) and Duncan's multiple range test (DNMRT) were employed ($P \leq 0.05$) to test the significance differences ($P \leq 0.05$) using Design Expert 6.0.8 and SPSS (IBM 21) statistical package, respectively. The main effects and two factors interactions were considered to determine the optimal outcomes of the treatments according Alabi et al. (2016).

Results and Discussion

Vitamin C

Figure 3 shows the effects of PMF intensity and treatment time on the vitamin C content of mangoes and tomatoes. From Fig. 3, it is shown that the change in vitamin C content was connected to magnetic field intensity as well as the duration of treatment. When the duration of the treatment reached 5 min, the vitamin C content of the mango and tomato increased with increase of the field intensity and reached the lowest values of 69.00 mg/100 g and 14.00 mg/100 g at 9 T for mango and tomato samples, respectively. When the duration of the treatment reached 10 min and 15 min, the vitamin C contents of the samples decreased slightly with the decrease in magnetic field intensity.

This suggests that PMF treatment has a significant influence the vitamin C level in both samples. The result aligned with Qiao et al. (2023) who reported that static magnetic field (SMF) intensity of 2–10 mT does not significantly ($P < 0.05$) reduced vitamin C content of Korla fragrant pear. Unlike the conventional freezing method that causes incomplete enzyme degradation, and gave higher vitamin C degradation in mango (Zhang et al., 2021b), PMF treatment of 9 T and 14 T slightly decreased the vitamin C content. The PMF treatment at 20 T created unique conditions in the water molecules within the mango and tomato samples, increased molecular vibration, and maintained the samples in a supercooled state. This supercooling effect delayed ice crystal formation, which is often responsible for nutrient degradation during freezing (Alabi et al., 2024). As a result, the retention of vitamin C is higher in PMF-treated samples, reaching 73.00 mg/100 g for mango and 16.00 mg/100 g for tomato, compared to untreated or fresh samples. In untreated samples, the vitamin C was more susceptible to degradation due to oxidation and enzyme activity during frozen storage.

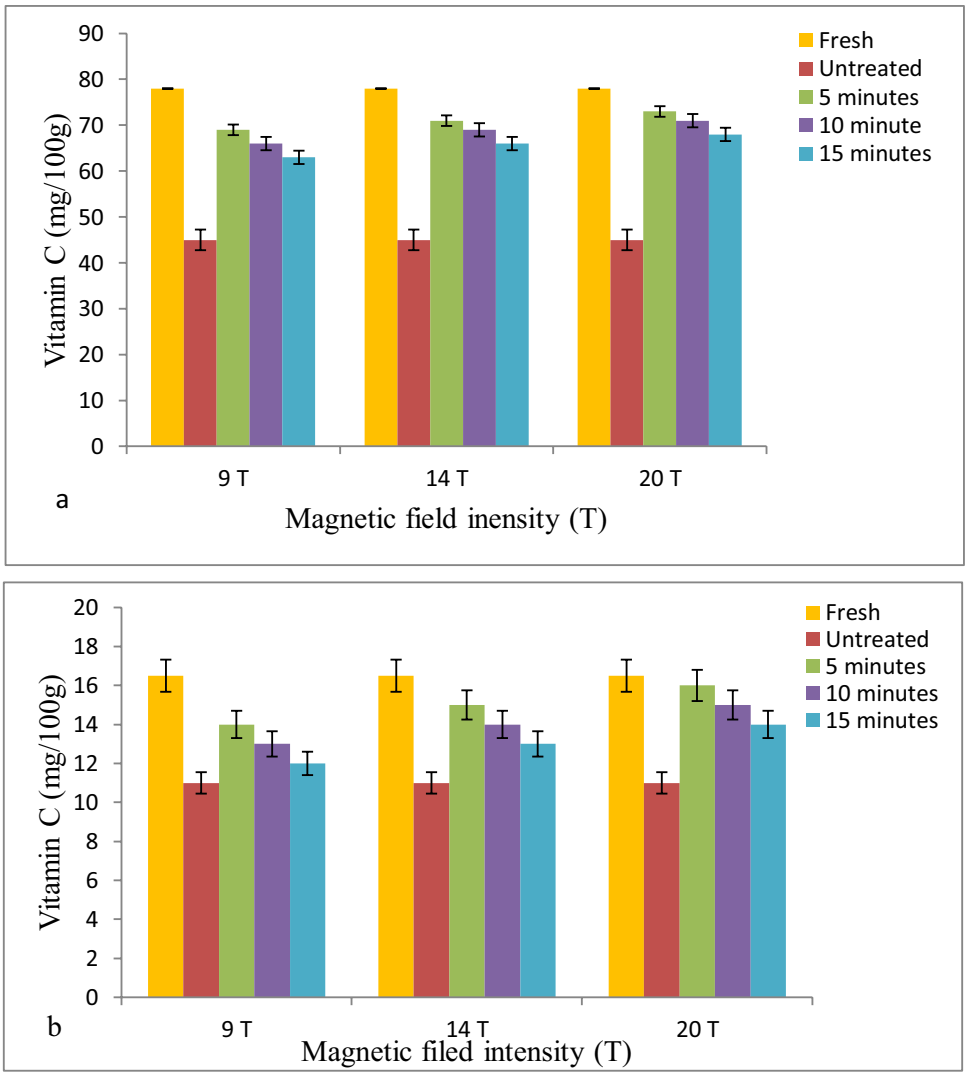


Fig. 3 Effect of PMF intensity and treatment time on the vitamin C levels in the frozen-thawed samples: **a** mango and **b** tomato

As a result, untreated frozen samples generally exhibited lower vitamin C content compared to fresh ones.

However, PMF treatment has a dual effect on vitamin C retention. When the magnetic field intensity or treatment time exceeds or falls below a certain threshold, it disrupted the equilibrium of the sample. If the treatment is too weak or too strong, it causes biochemical changes that reduced the vitamin C content instead of preserving it (Alabi et al., 2024). Therefore, there is an optimal range of PMF parameters—such as magnetic field intensity and duration of exposure—where the cumulative impact is beneficial. Outside of this range, the treatment may lead to a reduction in vitamin C levels, potentially rendering the treated fruits similar to, or even worse than, untreated samples in terms of nutrient retention. Thus, in comparison to fresh fruits, PMF-treated samples exhibited improved vitamin C retention when treated within optimal parameters, while untreated frozen fruits showed the most significant nutrient loss due to conventional freezing damage.

TSS

The combination of short pectin chains and cellulose in the absence of cellular moisture results in the coagulation of an extensive network of pectin chains, increasing TSS (Alabi et al., 2020). The freezing process at 20 T elevated the TSS levels of the stored mango and tomato, reaching 12 and 8°Brix, respectively (refer to Fig. 4). This increase is linked to treatment time, with longer duration (15 min) leading to a reduction in TSS. The treatment time demonstrated a significant impact on TSS levels for mango fruit ($P < 0.05$) (see Fig. 4a). The highest value, at 12°Brix was attained after a treatment time of 5 min, gradually decreasing as treatment extended to 15 min. However, the increase in TSS from 5 to 8°Brix exhibited a non-significant decline in treatment time ($P < 0.05$) for tomatoes (refer to Fig. 4b). This phenomenon is attributed to the gelling capability of pectin and cellulose in the stored samples (Charoenrein & Owcharoen, 2016).

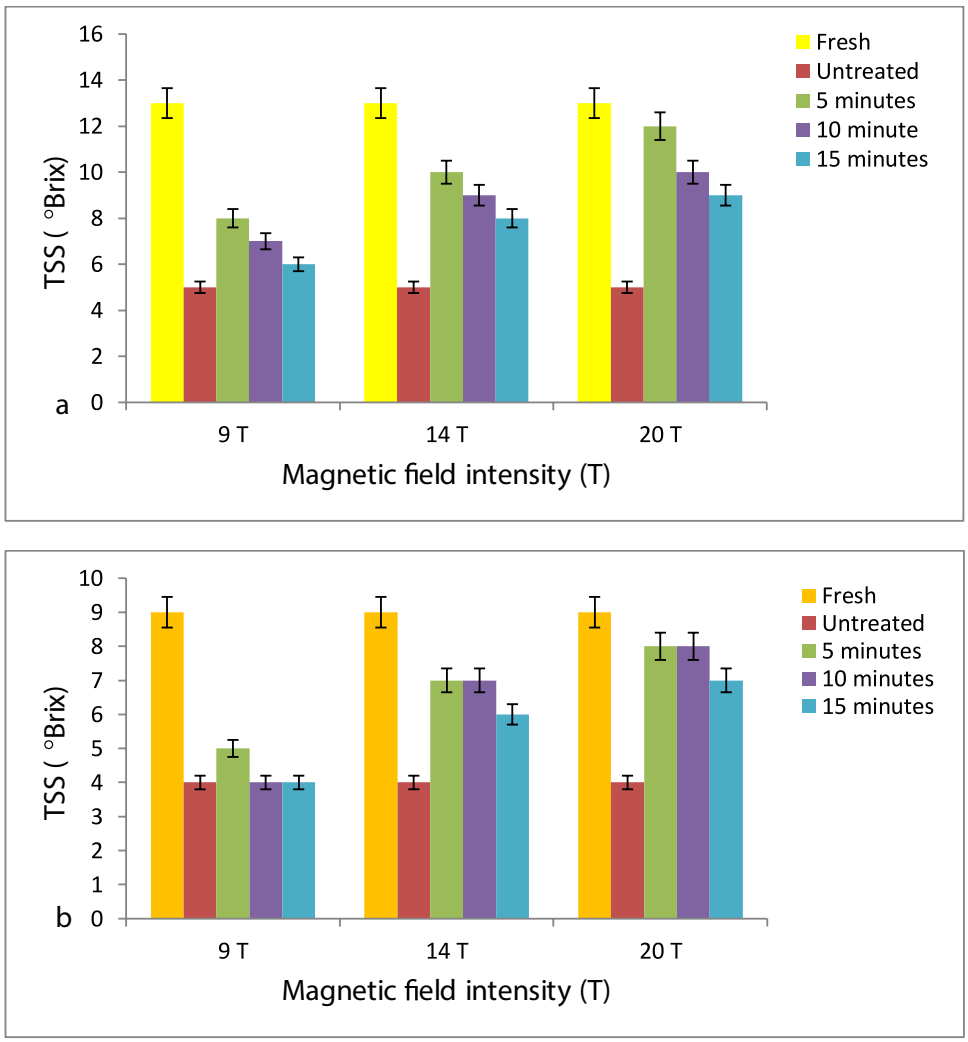


Fig. 4 Effect of PMF intensity and treatment time on the TSS content of frozen-thawed samples: **a** mango and **b** tomato

pH

The pH levels of PMF-assisted frozen samples were not substantially influenced by varying levels of magnetic field intensities and treatment time. Figure 5 shows the effect of the PMF intensity and treatment time on the pH levels of frozen-thawed mango and tomato.

The results showed that magnetic field treatment had no significant influence on the pH values of stored mango (4.8–5.0) (Fig. 5a) and tomato (4.75–4.9) (Fig. 5b). This is not in consistent with the findings of DeEll et al. (2000), who reported a significant difference in pH (4.9–6.9) between SMF-assisted hydrocooled and untreated cucumbers.

In another study by Zainal and Ding (2018), storage influences pH based on the weight loss of processed rockmelon. Zainal and Ding (2018) reported a significant effect on pH during the storage days of hydrocooled rockmelon fruits and their findings correlated changes in pH with an increasing trend of weight loss, measuring 1.40%, 1.68%, and 2.15% for storage periods of 1, 2, and 3 days, respectively.

Drip Loss

Figure 6 illustrates the effect of PMF intensity and treatment time on the drip loss values of the frozen-thawed mango and tomato.

In all treatments (9 T, 14 T, and 20 T), the PMF did not exert a significant difference in drip loss for the freeze-thawed mango and tomato, while untreated samples have higher drip loss values of 4.2% and 15.8%, for mango (Fig. 6a) and tomato (Fig. 6b), respectively. Drip loss varied between 2.5% and 2.2%, correlating to 9 T and 20 T PMF, respectively of the freeze-thawed mango. In addition, drip loss value of freeze-thawed tomato fluctuated from 12.8% to 10% which corresponded to 9 T and 20 T. The drip loss observed in the current study was lower than that reported for the Nam Dok Mai mango variety in previous studies, where cryogenic freezers were used, resulting in drip losses of 22.2% (frozen at − 40 °C and stored for 7 days) (Charoenrein & Owcharoen, 2016) and 18.7% (frozen at − 40 °C and stored for 30 days) (Sirijariyawat &

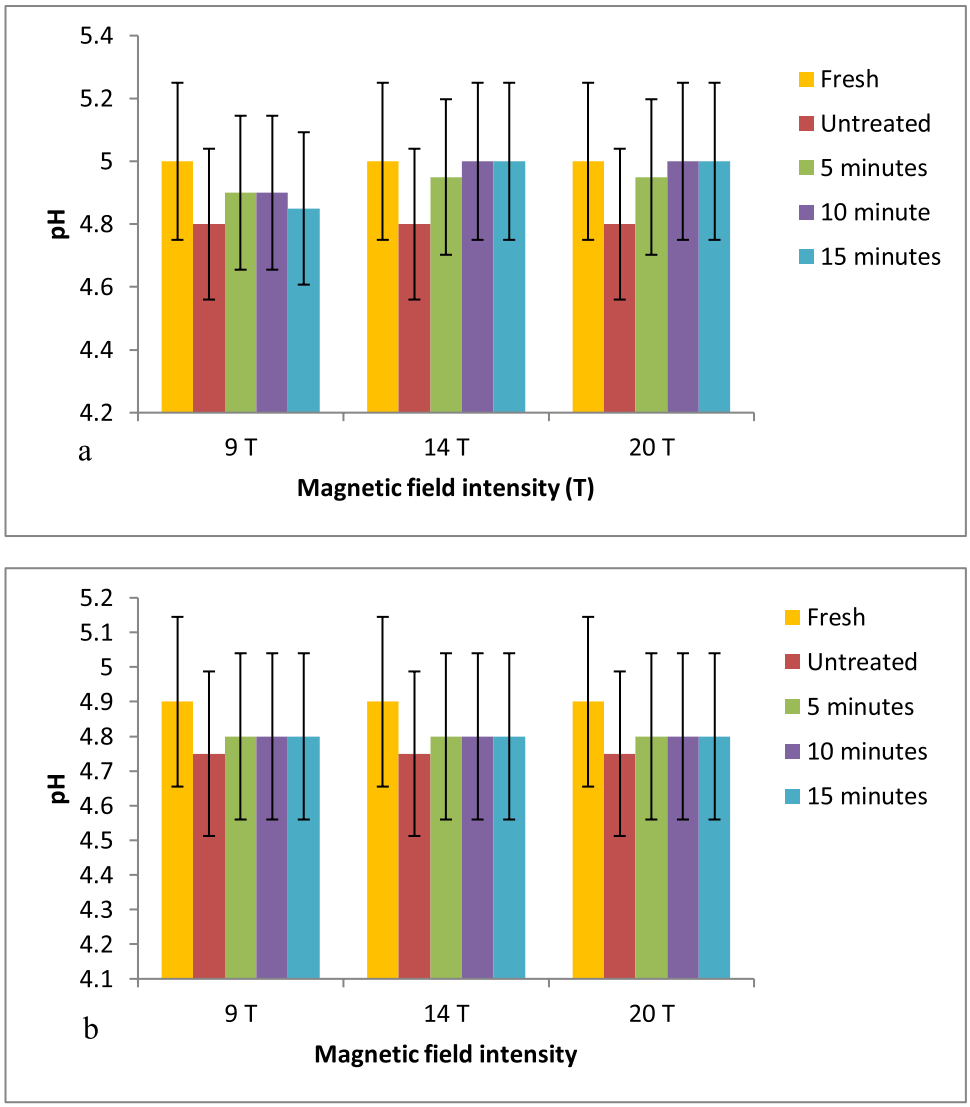


Fig. 5 Effect of PMF intensity and treatment time on the pH of frozen-thawed samples: **a** mango and **b** tomato

Charoenrein, 2012). This discrepancy in drip loss, compared to the cited studies, was attributed to the fact that samples were frozen (at – 18 °C) and thawed 14 days after freezing under ambient condition. In the study of Charoenrein and Owcharoen (2016), the liquid released from the interior to the exterior of the samples, due to damaged fruit cells, was attributed to uneven thawing. Another study by Purnell et al. (2017), which utilized OMF to assist in the freezing of apples and potatoes, reported drip loss values ranging from 9.4 to 10.5% for apples and from 10.0 to 13.7% for potatoes (frozen at – 30 °C) and thawed immediately. They indicated no significant difference for the majority of conditions under various levels of OMF. However, the findings in the present study, in conjunction with those reported by Purnell et al. (2017), suggest that different fruits exhibit varying drip losses because of uneven thawing.

Color Change

Color plays a crucial role in assessing the sensory quality of frozen products. The closer the color deviations are to the fresh samples, the more effective the freezing method. Color change (ΔE) values were measured immediately after treatment to assess the impact of magnetic field intensity and treatment time on the color attributes of frozen products. As depicted in Fig. 7, there was no significant difference in magnetic field intensity and treatment time on the color change values of the treated mangoes and tomatoes.

Fresh mango exhibited no noticeable color change, maintaining their brightness and vibrant appearance. This serves as the benchmark for assessing the effectiveness of both PMF treatments and the control samples. The closer the PMF-treated sample is to the fresh color, the more effective the treatment is at preserving visual quality. The

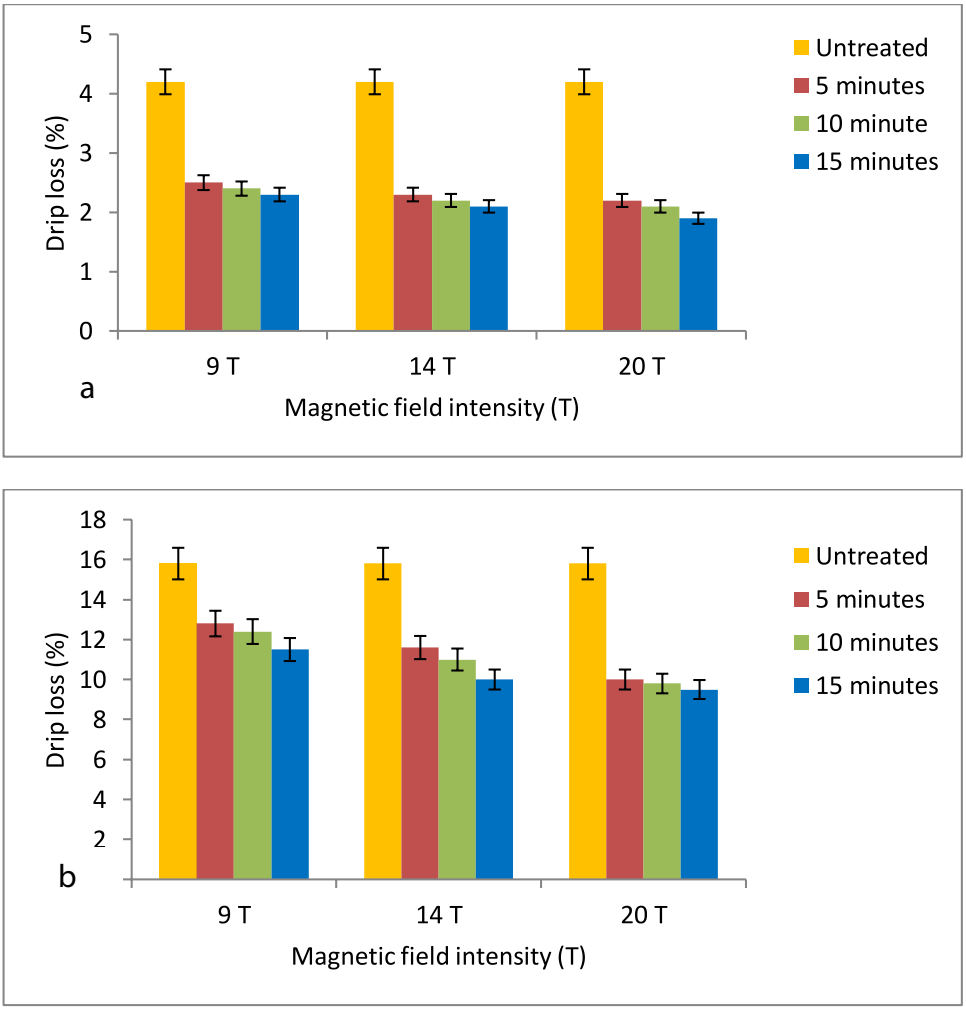


Fig. 6 Effect of PMF intensity and treatment time on the drip loss of frozen-thawed samples: **a** mango and **b** tomato

color change in mango samples was influenced by both the intensity of the magnetic field and the duration of treatment. Minimum color change (3.12) was observed when the samples were treated at 9 T for 15 min, suggesting a gentler impact on the mango's natural pigments. Minimal disruption to cellular structure during freezing and thawing under this condition reduced enzymatic browning, thereby maintaining closer to the original fresh sample color. Compared to the fresh mango, this treatment appears effective in maintaining color quality (refer to Fig. 7a). The highest magnetic field led to a more noticeable color change (4.32). At 20 T, the vibration of water molecules increased, which was effective in other areas like vitamin C retention, and it caused a more significant color change, moving further away from the natural appearance of fresh mango. The color change might be attributed to an increased rate of oxidation and possible disruption of cell membranes, allowing enzymes like polyphenol oxidase (PPO) to come into contact with phenolic compounds, initiating browning reactions (Tang et al., 2020a, 2020b). When compared to fresh mango, this treatment showed a significant deviation in color. Control (untreated) suffered the most color degradation due to ice crystal formation and enzymatic browning during thawing, exhibiting greater color change compared to both fresh and PMF-treated samples. This shows that while PMF treatments have beneficial effects on the retention of nutritional and textural qualities, color preservation is highly sensitive to the specific treatment parameters used. Additionally, it is evident from Fig. 7b that color change values increased with the rise in magnetic field intensity for tomato samples; however, the change is not significant for the combination of both treatments as shown in Table 2 in the appendix. Thus, it can be inferred from the current study that the magnetic field exposure significantly influences the color change of mango and tomato during freezing.

Firmness

As assessed with a texture meter, the treated frozen-thawed mango and tomato exhibited preserved firmness ($P < 0.05$) when compared to untreated (control) samples, likely

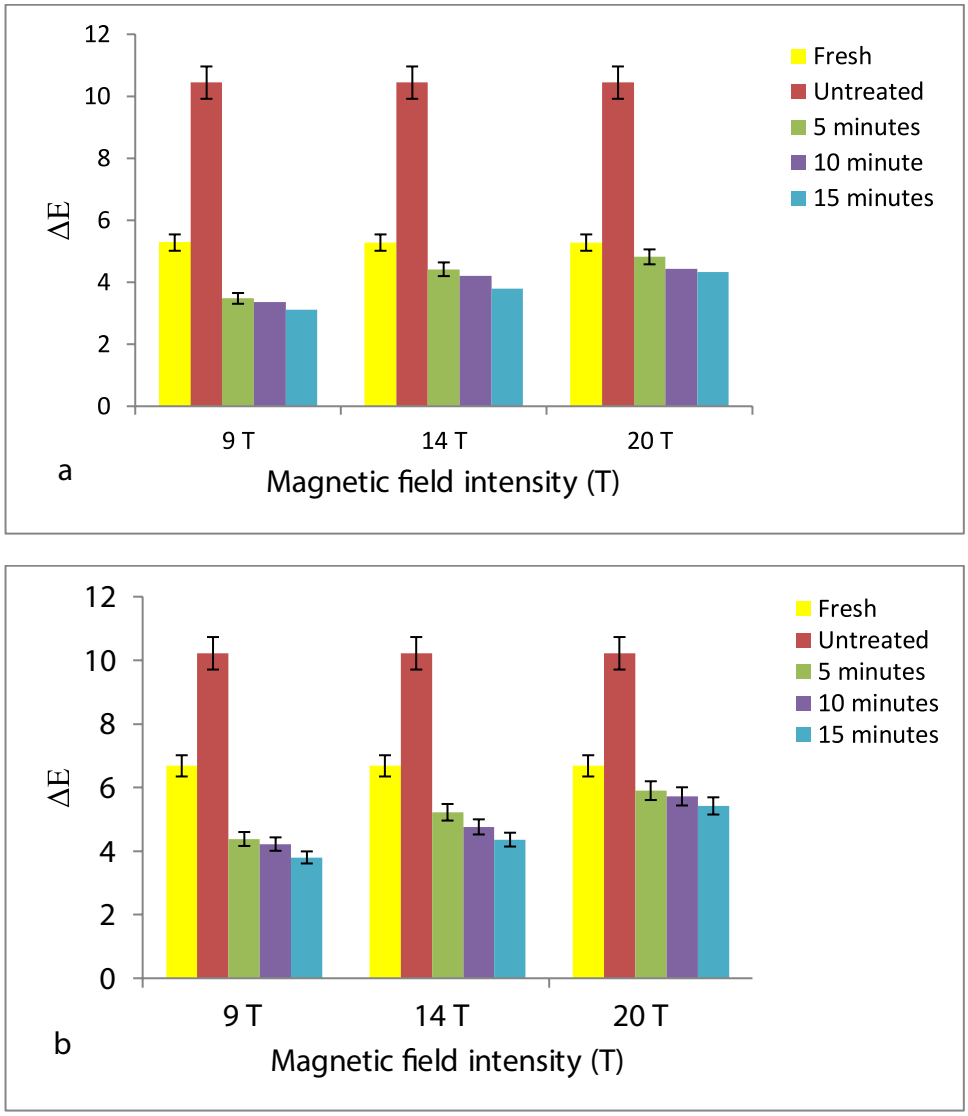


Fig. 7 Effect of PMF intensity and treatment time on the color change of frozen-thawed samples: **a** mango and **b** tomato

attributed to the formation of small ice crystals in the stored products. In Fig. 8, the results for all the treatments demonstrated a significant preservation of firmness in thawed mango and tomato ($P < 0.05$) after freezing (using various levels of PMF and time) in contrast to the control samples which exhibited lower firmness.

The observed slight decrease in firmness of both mango and tomato samples (from 3.6 to 3.5 N for mango and 6.2 to 5.8 N for tomato) after PMF pretreatment can be attributed to the weakening of the cellular structure, altered water mobility, changes in cell membrane permeability, and the influence on enzymatic activity. These factors combined lead to a minor reduction in firmness, but the overall quality can still be better preserved compared to untreated (control) samples due to the effects of PMF in moderating ice crystal formation during freezing. The preservation of firm using different levels of PMF pretreatment to freezing was similar to other studies involving emerging fast freezing. For instance, firmness was maintained in minimally processed guava (frozen at − 25 °C with an alternating magnetic field intensity of 2.4–8.8 mT) (Panayampadan et al., 2022) and fresh cut mango slices (frozen at − 5 °C with OMF intensity of 50 mT and stored for 7 days) (Kang et al., 2021). In those studies, the sustained firmness was attributed to the hurdle effect of freezing and storage. Similarly, the preservation of mango and tomato firmness primarily occurred due to the effect of freezing and storage assisted with PMF. Furthermore, the texture meter reported a maximum firmness of 3.5 N and 5.8 N for mango and tomato, respectively, in relation to the penetration depth (mm) for samples treatment with 20 T for 5 min. The depth penetrated by the texture meter probe in the thawed mango and tomato is depicted in Fig. 8. The difference in firmness observed in the treated frozen-thawed samples compared to fresh and control samples can be attributed to the nature of the cell structure of plants. These structures are composed of semi-rigid polyhedral

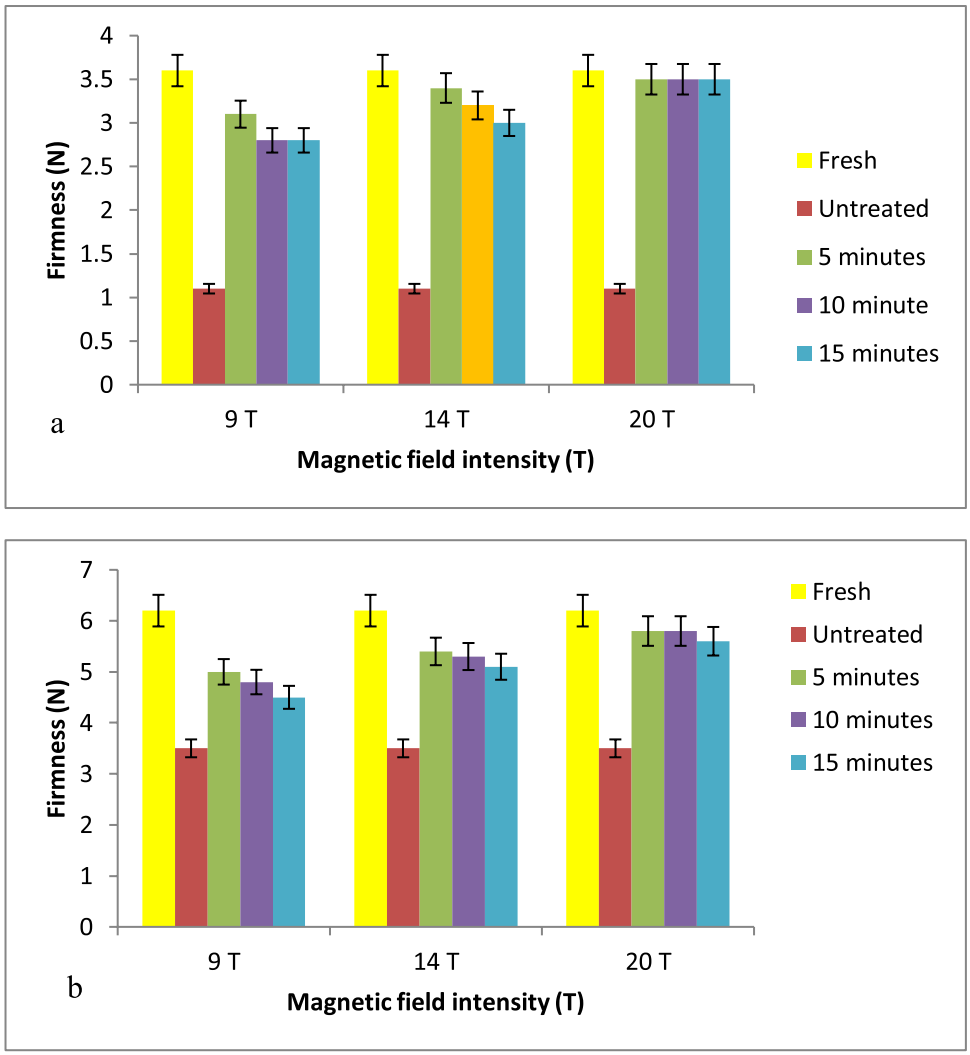


Fig. 8 Effect of PMF intensity and treatment time on the firmness of frozen-thawed samples: **a** mango and **b** tomato

cells containing cellulosic cell walls bound by various pectinaceous middle lamellae and often featuring an extensive network of air spaces (Otero et al., 2018; Rodríguez et al., 2019a, 2019b). More so, the higher the magnetic treatment time, the lower the friction coefficient and the less firm the final products (Wang et al., 2013).

Table 3 in the appendix displays the Duncan multiple range test (DMRT) results for the effect of PMF and treatment on some qualities of frozen-thawed samples. In summary, treated frozen-thawed samples exhibited greater firmness than untreated (control) frozen-thawed samples.

Conclusion

In conclusion, this study demonstrated that using a microcontroller-based pulsed magnetic field (PMF) pretreatment significantly enhanced the preservation quality of frozen-thawed mango and tomato. By applying different field intensities (9 T, 14 T, and 20 T) and treatment durations (5, 10, and 15 min), it was observed that the PMF pretreatment improved key quality parameters like vitamin C content, total soluble solids (TSS), firmness, and color while reducing drip loss. The results showed that the optimal conditions were achieved at a field intensity of 20 T for 5 min, which preserved the quality of the fruits better than untreated samples. This pretreatment method has potential for extending the shelf life and maintaining the quality of frozen fruits and vegetables, making it a promising technique for the food preservation industry. For complete comprehension of the technique, the effect of PMF intensity and treatment time on the texture, flavor, and biochemical properties of frozen mango and tomato is recommended for further study.

Abbreviation: *AC*, alternating current; *DC*, direct current; *OMF*, oscillatory magnetic field; *CAS*, cell alive system; *PMF*, permanent magnetic field; *AMF*, alternating magnetic field

Appendix

Table 2 Analysis of variance (ANOVA) of the effect of PMF and treatment time on some qualities of frozen-thawed mango and tomato

Sample	Physicochemical properties	Process variables		Interactions
		A	B	AB
Mango	Vitamin C (mg/100 g)	0.0001*	0.0001*	0.4568
	TSS (°Brix)	0.0002*	0.0001*	0.3144
	pH	0.3228	0.0013*	0.0709
	Drip loss (%)	0.0002*	0.0001*	0.3144
	Color change	0.0033*	0.0001*	0.6334
	Firmness (*N*)	0.2882	0.0008*	0.0068*
Tomato	Vitamin C (mg/100 g)	0.0001*	0.0001*	0.8712
	TSS (°Brix)	0.0026*	0.0001*	1.0000
	pH	0.0001*	0.0001*	0.4523
	Drip loss (%)	0.0001*	0.0001*	0.0477*
	Color change	0.0001*	0.0001*	0.6658
	Firmness (*N*)	0.0001*	0.0001*	0.0071*

*Significant different at $P \leq 0.05$

Where A = treatment time, B = PMF intensities

Table 3 Duncan multiple range test (DMRT) of the effect of PMF intensity and treatment time on some qualities of frozen-thawed mango and tomato

Treatments			Vitamin C (mg/100 g)		TSS(°Brix)		pH		Drip loss (%)		Color change ΔE		Firmness (*N*)	
Intensity/treatment time			Mango	Tomato	Mango	Tomato	Mango	Tomato	Mango	Tomato	Mango	Tomato	Mango	Tomato
	Control		45.00 ± 02^{c}	11.00 ± 02^{c}	5.06 ± 01^{c}	4.72 ± 01^{c}	4.80 ± 01^{c}	4.75 ± 01^{b}	4.20 ± 01^{a}	15.80 ± 01^{a}	10.44 ± 03^{a}	10.22 ± 03^{a}	1.10 ± 04^{c}	3.50 ± 04^{c}
	9 T	5 min	69.00 ± 02^{b}	14.01 ± 02^{b}	8.00 ± 01^{a}	5.11 ± 01^{c}	4.90 ± 01^{b}	4.80 ± 01^{a}	2.50 ± 01^{b}	12.80 ± 01^{b}	3.48 ± 03^{c}	4.38 ± 03^{c}	$3.10 \pm 04^{b,c}$	$5.00 \pm 04^{a,b}$
		10 min	66.66 ± 02^{b}	13.41 ± 02^{b}	7.66 ± 01^{b}	4.01 ± 01^{c}	4.90 ± 01^{b}	4.80 ± 01^{a}	2.40 ± 01^{b}	12.40 ± 01^{b}	3.36 ± 03^{b}	4.22 ± 03^{c}	2.80 ± 04^{c}	4.80 ± 04^{c}
		15 min	63.66 ± 02^{c}	12.21 ± 02^{c}	6.66 ± 01^{c}	4.01 ± 01^{c}	4.85 ± 01^{b}	4.80 ± 01^{a}	2.30 ± 01^{b}	11.50 ± 01^{b}	3.12 ± 03^{c}	3.80 ± 03^{c}	2.80 ± 04^{c}	4.50 ± 04^{c}
	14 T	5 min	71.66 ± 02^{a}	15.21 ± 02^{a}	10.00 ± 01^{b}	7.01 ± 01^{a}	4.95 ± 01^{a}	4.80 ± 01^{a}	2.30 ± 01^{b}	11.60 ± 01^{b}	4.42 ± 03^{b}	5.22 ± 03^{b}	3.40 ± 04^{a}	5.40 ± 04^{b}
		10 min	69.56 ± 02^{b}	14.13 ± 02^{b}	9.01 ± 01^{b}	7.14 ± 01^{b}	5.00 ± 01^{a}	4.80 ± 01^{a}	2.20 ± 01^{b}	11.00 ± 01^{b}	4.20 ± 03^{b}	4.76 ± 03^{b}	3.20 ± 04^{a}	5.30 ± 04^{b}
		15 min	66.97 ± 02^{c}	13.01 ± 02^{b}	8.66 ± 01^{b}	6.14 ± 01^{b}	5.00 ± 01^{a}	4.80 ± 01^{a}	2.10 ± 01^{c}	$10.00 \pm 01^{b,c}$	3.80 ± 03^{b}	4.36 ± 03^{c}	$3.00 \pm 04^{b,c}$	$5.10 \pm 04^{a,b}$
	20 T	5 min	73.66 ± 02^{a}	16.01 ± 02^{a}	12.33 ± 01^{a}	8.66 ± 01^{a}	4.95 ± 01^{a}	4.80 ± 01^{a}	2.20 ± 01^{b}	$10.00 \pm 01^{b,c}$	4.82 ± 03^{b}	5.90 ± 03^{b}	3.50 ± 04^{a}	5.80 ± 04^{a}
		10 min	71.72 ± 02^{a}	15.00 ± 02^{a}	10.87 ± 01^{a}	8.68 ± 01^{a}	5.00 ± 01^{a}	4.80 ± 01^{a}	2.10 ± 01^{c}	9.80 ± 01^{c}	4.44 ± 03^{b}	5.72 ± 03^{b}	3.50 ± 04^{a}	5.80 ± 04^{a}
		15 min	68.21 ± 02^{b}	14.01 ± 02^{b}	9.77 ± 0^{b}	8.18 ± 01^{a}	5.00 ± 01^{a}	4.80 ± 01^{a}	1.9 ± 01^{c}	9.50 ± 01^{c}	4.32 ± 03^{b}	5.42 ± 03^{b}	3.50 ± 04^{a}	5.60 ± 04^{a}

*Samples with the same superscript are not significantly different

Author Contribution Kehinde Peter Alabi conceived and developed the microcontroller PMF-assisted freezing device, carried out the experiment and performed data analysis, write initial version, and Ayoola Patrick Olalusi supervised while John Isa conducted editing, and acquired journals, books, and conference proceedings. Kehinde Folake Jaiyeoba did the editing and co-supervision.

Data Availability Data is provided within the manuscript.

Declarations

Competing Interests The authors declare no competing interests.

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