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Effects of pulsed magnetic field intensity on the freezing rate and heat loads reduction of harvested mango and tomato

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Abstract

Purpose – Fresh fruits and vegetables (FV) are crucial global food resources, but the presence of heat loads during harvest adversely impacts their shelf life. While freezing technology provides an effective means of removing heat loads, it is an energy-intensive process and may consequently prove too costly for practical business viability. The growing interest in utilizing magnetic field (MF) technology during the freezing of fresh FV enhances the freezing rate and rapidly removes the heat loads of products.

Design/methodology/approach – In the present study, pulsed magnetic field (PMF) pretreatment employing specific field strengths (9 T, 14 T and 20 T) was examined as a preliminary step before freezing mango and tomato and compared to the conventional freezing method (untreated) at − 18 °C.

Findings – PMF pretreatment prior to freezing demonstrated a noteworthy enhancement in freezing rate by around 10 and 12% when compared with the conventional (untreated) freezing, which exhibited freezing rates of −0.08 °C/min and −1.10 °C/min for mango and tomato, respectively. The PMF pretreatment (at 20 T) provided a higher freezing rate (at $p = 0.05$) than the conventional freezing method reduced heat loads amounting to 1.1 × 107 J/kg oC and 2.9 × 106 J/kg oC, significantly (at $p = 0.05$) from mango and tomato, respectively. These reductions in heat loads were approximately more than 5% of the calculated heat loads removed during conventional freezing.

Research limitations/implications – Mango and tomato samples were only tested; the results may lack generalizability. Therefore, researchers are encouraged to test for other products for further studies.

Practical implications – The paper includes implications for the development of a rapid freezing technique, the development of "pulsed magnetic field" and for eliminating the problem associated with conventional (slow) freezing.

Originality/value – The study holds significance for the production of postharvest freezing technology, providing insightful information on the PMF-assisted freezing of cellular foods.

Keywords Fruit and vegetables, Freezing, Magnetic field, Heat loads, Postharvest

Paper type Research paper

1. Introduction

The overall condition of frozen foods, particularly fruits and vegetables (FV), is influenced by the freezing process. The freezing process of FV involves pre-freezing, freezing and frozen storage (Alabi *et al.*, 2020, 2022; Kang *et al.*, 2020; Pham, 2018; Zhang *et al.*, 2020). Studies have shown that the freezing process greatly impacts senescence, enzyme activity and shelf life of FV (Panayampadan *et al.*, 2022; Qiao *et al.*, 2023; Tang *et al.*, 2020; Tian *et al.*, 2020; Wu *et al.*, 2022). Using the freezing process of cellular foods as an illustration, it

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is essential to rapidly lower their temperature to below 4 °C immediately after harvest, given their perishable nature and the objective of removing the sensible (field) heat, thus extending their shelf life (Alabi *et al.*, 2021; Cantre *et al.*, 2017; Devani and Karetha, 2011; Fan *et al.*, 2020; Kasso and Bekele, 2018; Santos *et al.*, 2020; Zainal *et al.*, 2019). Subsequently, fresh FV should be frozen-stored at a temperature of −18 °C or below (Alabi *et al.*, 2022). Throughout the freezing process, as the temperature of the sample decreases, the water within it undergoes a phase transition from liquid to solid, resulting in the formation of ice crystals (Alabi *et al.*, 2020). Ice crystals inflict harm on microbial cells, resulting in the total elimination of harmful microbes in products. Conventionally, the freezing process is slow and can cause non-uniformly distributed large ice crystals, resulting in damage to the cell structure of FV (Li *et al.*, 2018). Thus, there is a need to contemplate methods to enhance the freezing process of FV. This would facilitate a swift traversal through the region where maximum ice crystal formation occurs, thereby diminishing the formation of large ice crystals. Such an approach mitigates the adverse effects of ice crystals on cellular foods *(*Alabi *et al.*, 2023). The FV freezing process can be categorized primarily based on freezing rate into two groups: fast freezing (−4.5 °C/min to −2.0 °C/min) and slow freezing (−0.20 °C/min to −0.05 °C/min), producing varying size and shape of ice crystals (Alabi *et al.*, 2020; Tang *et al.*, 2020). Fast freezing, considered a novel freezing technology, can swiftly lower the temperature of the cellular food center to below −18 °C, leading to the creation of small ice crystals. This approach serves the purpose of expedited food freezing, contributing to the reduction of heat loads and cell damage (Zhang *et al.*, 2021). For instance, Tang *et al.* (2020) investigated the impact of the fast freezing method, through the use of a permanent magnetic field and an alternating magnetic field, on the freezing temperature and cooling rate of cherry. Some important factors, such as phase change time, ice crystals formed and drip loss value in cherry frozen at different field intensities, were examined. Their findings revealed that fast freezing was achieved in the presence of an alternating magnetic field of 1.26 mT and produced uniformly ice crystals, which reduced drip loss to some extent, with consideration given to energy-saving factors. However, the study did not elaborate on the variations in freezing rate and heat loads resulting from freezing of cherry. Giudici *et al.* (2021) conducted mathematical modeling of the crystallization process occurring during batch production of ice cream. They validated the models with a unique pattern recognition algorithm to effectively describe the main steps of crystallization kinetics. However, their study did not provide information on the heat loads for the freezing process to enable effective prediction of energy consumption during the production of ice cream.

In order to envisage the working efficiency of an air freezing system using R22 and R404a refrigerants, Nguyễn (2024) employed an energy and exergy study to analyze the change in freezing time and energy consumption for the freezing system in freezing conditions at temperatures from −30°C to −45°C with an air velocity of 6 m/s. Similarly, Narsaiah *et al.* (2021) conducted heat transfer modeling on frozen shrimp in a cryogenic freezing system, predicting core temperature distribution at seven different locations of the freezer. However, their study lacked experimental validation and analysis of how freezer conditions influenced shrimp's heat load level. Hence, investigating the heat loads of foods during freezing is crucial to the production of effective postharvest technology. In order to discover more energy-efficient postharvest freezing techniques, this study aims to investigate the effects of pulsed magnetic field (PMF) intensity on the freezing rates and heat loads removed during the freezing process of mangoes and tomatoes. The objective is to offer an experimental benchmark for the freezing rate and gain insight into the heat load content removed during the freezing process of mango and tomato. Additionally, the study seeks to elucidate conditions that allow samples to traverse the maximum ice crystal formation zone swiftly and ensure quality while removing heat content of products.

2. Material and method

2.1 Materials

The materials employed in the freezing experiment assisted by PMF treatment are detailed in Alabi *et al.*'s (2023b) work. Additionally, other materials utilized in the experiment include: mangoes, tomatoes, a sensible weighing balance (SF-400 Beichen 0–1000 g, Zhejiang, China), a digital thermometer (HTC 2, Zhejiang, China), stainless plates, food-grade hand gloves and a freezing machine (NX-160HC, Guanzhou, China). Figure 1 shows the configuration of the freezing technique assisted with a pulsed magnetic field.

2.2 Experimental procedure

Fresh mango (*Mangifera indica*) and tomato (*Solanum lycopersicum*) were acquired from a local market in Malete, Nigeria, situated at coordinates 51° 27′ 49.144″ N and 19° 13′ 4.303″ E. Subsequently, the specimens were transported to the laboratory at the Department of Food and Agricultural Engineering, Kwara State University (KWASU). The samples underwent cleaning using absorbent paper. The PMF-assisted freezing process involved exposing the samples to PMF with intensities of 9 T, 14 T and 20 T. This induced a magnetic dipole moment through wave vibrations across product masses, leading to electron spins and the creation of additional hydrogen bonds in the samples, thereby enhancing the freezing process. PMF intensities were determined by the number of turns of the transformer and measured using a Gauss meter. Mangoes and tomatoes, weighing 100 ± 1 g and 25 ± 1 g, respectively, were subjected to two process conditions: (1) PMF treatment for 5 min followed by freezing at −18°C and (2) Conventional (control) freezing at −18°C. The PMF freezing experiments were carried out in triplicate. Standard methods were employed to measure the freezing rate and heat load of each sample.

2.3 Freezing rate

The freezing rate was calculated by dividing each temperature data point by its corresponding time point according to Alabi *et al.* (2023a), using Equation (1).

$$\text{Freezing rate } (℃/sec) = \frac{\Delta T}{\Delta t} \tag{1}$$

Where ΔT is change in temperature (°C), and Δt is change in time (sec)



Source(s): Authors' work

Figure 1.
Configuration of the freezing technique assisted with pulsed magnetic field: a – fresh samples, b – microcontroller-based pulsed magnetic field pretreatment device, c – data acquisition system, d – freezing machine and e – frozen storage apparatus

2.4 Heat loads

The heat loads were calculated according to the freezing process in three phases, namely, (1) reduction of product temperature from harvested/ambient temperature to the freezing temperature to remove sensible heat (known as field heat), (2) removal of the latent heat at the freezing temperature as the product freezes and (3) removal of latent heat to reduce the frozen product to the final sub-freezing temperature, as described by Krishnakumar and Dayanandakuma (2017) in Equations (2-4), respectively.

$$\textit{Heat load during cooling} = MC_a\Delta\theta \tag{2}$$

$$\textit{Heat load during phase change} = M_{L_f} \tag{3}$$

$$\textit{Heat load during sub freezing} = M_{L_v} \tag{4}$$

$$\textit{Total heat load} = \textit{Sensible heat remove to reach to freezing temperature} + \textit{latent heat remove at phase change} + \textit{heat remove at sub freezing stage}$$

$$\textit{Total heat loads} = MC_a\Delta\theta + M_{L_f} + M_{L_v}$$

Where;

M is the weight of the sample

C_a is the specific heat of sample above freezing

$\Delta\theta$ is temperature difference

C_b is the specific heat of sample below freezing

L_f is the latent heat of fusion

L_V is the latent heat of vaporization

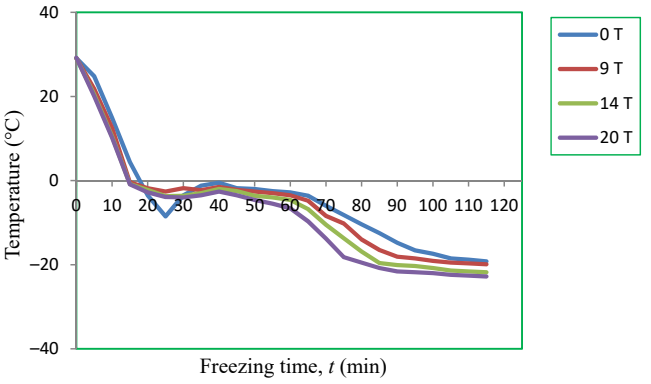
2.5 Statistical analysis

All measurements taken from the experiments were analyzed in terms of the effect of PMF on the freezing rate and heat load reduction during the freezing process of mango and tomato. The PMF intensities were selected as fixed factors. The freezing rate and heat loads reduced, including sensible heat, latent heat of fusion and latent heat of evaporation, were taken as response variables. One-way ANOVA was employed using the SPSS (IBM 21) statistical package, and the significance was set at the level of 0.05.

3. Results and discussion

3.1 Freezing rate

In general, the freezing process can be roughly divided into three stages, namely, the cooling phase, the phase change stage and the sub-freezing phase (Alabi *et al.*, 2020). It is widely known that freezing time affects the size of ice crystals and the shorter the freezing process, the finer the ice crystals and the more evenly distribution, which is expected to produce high frozen product quality of food materials (Alabi *et al.*, 2022; Parniakov *et al.*, 2015). Figure 2 shows the freezing rate of mango under different PMF intensities. At the cooling phase, the freezing curves of different treatments showed almost overlapping, which meant there was no significant difference among the groups during this period. After reaching the freezing point of −0.8 °C, the phase transition began and the latent heat of crystallization was released. At this stage, the central temperature remained almost constant and the freezing rate was basically the same. Nearly 80% of the water was frozen into ice when the sample

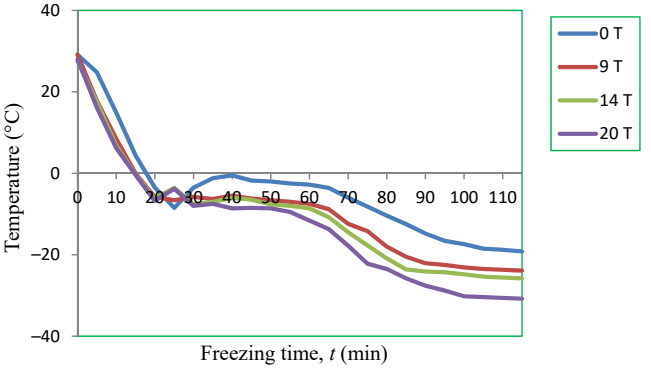


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Figure 2.
Freezing rate of mango

center temperature dropped from −0.8 °C to −18 °C, and a higher freezing rate of −3.5 °C/min was observed when the sample was treated with PMF of 20 T than the freezing rate of −0.08 °C/min observed for untreated samples. This temperature interval and high freezing rate support the creation of small, numerous ice crystals (Tang *et al.*, 2020; Zhang *et al.*, 2021). The observation is in agreement with Qiao *et al.* (2023), who reported that the rapid passage of the maximum ice crystal formation zone promotes the formation of small ice crystals and is the main factor that contributed to the high quality of frozen Korla fragrant pear. For the freezing process of the tomato sample, it came with the cooling stage, and then the temperature rose to the sample freezing point of about −0.3 °C, as shown in Figure 3. After that, there exist slight temperature drops until it became almost constant at around −18 °C. At this stage, the samples frozen under different PMF intensities went through a phase transition stage with different lengths, where significant differences in freezing rates among the groups occurred.

As indicated in Figure 3, the maximum ice crystal formation zone corresponding to the treatment groups with the higher PMF intensity had a faster freezing rate of −4.5 °C/min and an earlier onset and shorter duration occurred at all stages.



Source(s): Authors' work

Figure 3.
Freezing rate of tomato

The control group (without PMF) passed this band in 70 min with a freezing rate of −1.10 °C/min, and the time duration of the 9, 14 and 20 T PMF-treated groups was 26, 24 and 18 min, respectively. The results indicated that when the PMF strength reached 20 T, it effectively promoted the rapid formation of large numbers of small ice crystals that is required in improving the quality of frozen products. Tang *et al.* (2020) reported that the reason why the freezing process was affected drastically in tomatoes is due to the probability of reduction in the binding of the water molecules in cherry-like products after magnetic field exposure. At the freezing phase, it was evident from Figures 2 and 3 that all tested PMF intensities, except the 9 T, promoted the freezing rate and shortened the freezing time compared to the directly frozen control group. Table 1 shows the Duncan's multiple range test (DMRT) of the effect of PMF treatment on the freezing rates of mango and tomato. The freezing rate was faster with gradually increased PMF intensities, which suggested that the PMF treatment facilitated the freezing process of the mango and tomato samples. However, the freezing rate was slower in the control for both samples. The PMF intensity of 9 T did not significantly increase the freezing rate, whereas the strength of the PMF at 20 T accelerated the freezing process of both products.

3.2 Heat loads

The PMF pretreatment removed the heat loads of the two samples significantly. As shown in Table 2, the total heat loads removed were 9.2×10^6 J/kg °C, 9.8×10^6 J/kg °C and 1.1×10^7 J/kg °C when mango was pretreated at 9 T, 14 T and 20 T, respectively. Moreover, the

Table 1.
Duncan's multiple range test (DMRT) of the effect of PMF treatment on the freezing rates of mango and tomato

Sample/treatments		Freezing rate (°C/min)
Mango	Control	-0.08 ± 0.2^a
	9 T	-0.10 ± 0.2^a
	14 T	-3.30 ± 0.2^b
	20 T	-3.50 ± 0.2^b
Tomato	Control	-1.10 ± 0.3^a
	9 T	-1.15 ± 0.3^a
	14 T	-3.40 ± 0.3^b
	20 T	-4.50 ± 0.3^b

Note(s): *Samples with the same superscript are not significantly different
Source(s): Authors' work

Table 2.
Average sensible heat (J/kg°C), average latent heat of fusion (J/kg°C) and average latent heat of evaporation (J/kg°C) removed during the freezing process of mango and tomato under different magnetic field intensities

Sample/treatments		Sensible heat (J/kg°C)	Latent heat of fusion (J/kg°C)	Latent heat of evaporation (J/kg°C)	Total heat loads (J/kg°C)
Mango	Control	6.3×10^6	6.5×10^4	7.0×10^4	6.4×10^6
	9 T	9.0×10^6	9.3×10^4	9.2×10^4	9.2×10^6
	14 T	9.5×10^6	2.0×10^5	9.5×10^4	9.8×10^6
	20 T	1.1×10^7	2.1×10^5	2.0×10^5	1.1×10^7
Tomato	Control	1.4×10^6	1.6×10^4	1.8×10^4	1.4×10^6
	9 T	2.2×10^6	4.3×10^4	2.6×10^4	2.3×10^6
	14 T	2.5×10^6	5.6×10^4	3.9×10^4	2.6×10^6
	20 T	2.8×10^6	8.3×10^4	4.7×10^4	2.9×10^6

Note(s): *Standard error = 0.24
Source(s): Authors' work

experiment shows that the high magnetic field intensity achieves better heat load removal and will be a novel direction of the development of a fast freezing technique.

The heat load reduction analysis showed a fast evolution of substantive heat from the frozen samples, which can cause minimal cell degradation as supported by the high freezing rates under PMF treatment at 20 T. On the other hand, conventional freezing resulted in small heat reductions from the samples, as caused by slower freezing rates for both samples. However, the findings in the present study are in agreement with the results of Kamińska-Dwórznicka *et al.* (2023), who reported that fast freezing by ultrasound assistance (at 21.5 kHz) of mango sorbet reduced freezing time and caused a most uniform crystal structure with an equivalent diameter of 9 μm when compared to the equivalent diameter of 25 μm produced under conventional freezing.

Therefore, magnetic field-assisted freezing was found to have a positive effect on the freezing rates, where huge amounts of heat were gradually removed from fresh FVs after harvest. The effect of the PMF pretreatment on the freezing rate and heat loads reduction of the samples is based on the predominant constituents of cellular foods – specifically, magnetic elements or ions and water. Fruits and vegetables comprise a significant amount of water molecules, often ranging from 80% to 90% in content (Alabi *et al.*, 2020). When dipolar water molecules are subjected to an external magnetic field, an electromotive force is applied to either charge of the polar molecule, increasing the number of hydrogen bonds and inducing vibration or rotary movement of the charge center in the direction of the field (Otero *et al.*, 2016; Tang *et al.*, 2020). The higher the magnetic intensity, the higher the energy. The higher the energy, the faster the movements of molecules and the more rapid the heat transfer and vice versa.

4. Conclusion

In an attempt to ensure shortest processing time, low cost and high efficiency in terms of energy use during freezing of fruits and vegetables, a PMF treatment technique was applied prior to freezing of mango and tomato. The technique was operated at three different magnetic field intensities of 9 T, 14 T and 20 T. The freezing rates and heat load reduction of the technique were investigated and compared with the conventional slow freezing method. As the field intensity increases, the freezing rate increases and reaches −3.5 °C/min and −4.5 °C/min for mango and tomato, respectively, at a PMF treatment of 20 T. More so, total heat loads, including sensible heat, latent heat of fusion and latent heat of evaporation, of 1.1×10^7 J/kg°C and 2.9×10^6 J/kg°C were removed from mango and tomato, respectively, at the highest field intensity. Though the technique increases the freezing rate of mango and tomato and greatly removes a higher amount of heat loads present in samples at the fastest rate, future work should focus on the effect of different magnetic fields on the quality of the frozen products.

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