Agr. Foo. Nat. Res. J. Volume 4, Issue 1, Page 71 - 78

e-ISSN: 1597-7153 | p-ISSN: 3043-5420

Agriculture, Food and Natural Resources Journal

The Official Journal of the Faculty of Agriculture, Nnamdi Azikiwe University, Awka, Nigeria

Journal homepage: https://journals.unizik.edu.ng/afnrj

Original Article

Fast freezing induced by magnetic field: impact of field intensity and exposure time on the quality characteristics of frozen pineapple

Kehinde Peter ALABI[1]*, Kazeem Koledoye OLATOYE[2], Oyediran Promise OYEBADE[1], Abdulqadir Tosho OPOBIYI[3] & Adeoye Ibukun OYEBANJI[4]

[1]*Department of Food and Agricultural Engineering, Kwara State University, Malete P.M.B. 1530, Ilorin, Kwara State, Nigeria*
[2]*Department of Food Science and Technology, Kwara State University, Malete P.M.B. 1530, Ilorin, Kwara State, Nigeria*
[3]*Ministry of Agriculture, Ilorin, P.M.B. 1383 Old Jebba Road, Kwara State Nigeria*
[4]*Postharvest Engineering Research Department, Nigerian Stored Product Research Institute,Km 3 Asa Dam Road, P.M.B. 1489, Ilorin, Kwara State, Nigeria*

DOI: https://www.doi.org/10.5281/zenodo.15106954

Editor: *Dr Onyekachi Chukwu, Nnamdi Azikiwe University, NIGERIA*

Received: *November 27, 2024*
Accepted: *February 13, 2025*
Available online: *March 31, 2025*

Peer-review: *Externally peer-reviewed*

Conflict of Interest: The authors have no conflicts of interest to declare

Financial Disclosure: *The authors declared that this study has received no financial support*

ABSTRACT

This study investigated the impact of magnetic field (MF) intensity and time on the quality characteristics of frozen pineapple. Raw pineapple was washed, peeled and sliced. The pineapple slices with thickness of 10×10×10 mm cube were exposed to magnetic field intensities of 9 T, 14 T, and 20 T and exposure times of 5, 10, and 15 minutes before they underwent freezing at -18oC. Fresh and untreated frozen samples were regarded as control 1 and control 2, respectively. The quality characteristics including pH, firmness, total soluble solids (TSS), and microstructure were measured using standard methods. The results indicated that MF intensity and exposure time had non-significant (at P≤5) effect on the pH of the slices. However, significant improvements were noted in firmness and TSS of treated samples when compared to the control groups. Scanning electron microscopy (SEM) revealed that MF treatment, particularly at higher field intensities of 14 T and 20 T, and shorter treatment time of 5 minutes, produced small ice crystals, and aided preservation of cell structure, resulting in minimal tissue damage. These findings suggest that MF technology could serve as a viable non-thermal technique that enhances the quality of fruits, with potential applications in the food industry.

KEYWORDS: *Firmness, Microstructure, Ice crystal, pH, Tissue damage*

INTRODUCTION

Pineapple (*Ananas comosus*) is a popular tropical fruit known for its sweetness, strong flavor and high nutritional value (FAO, 2019; Yahia *et al*., 2019). However, its high water content and delicate cell structure makes it prone to spoilage, requiring effective preservation methods. Freezing is commonly used to maintain flavor, nutritional value, and texture, but it can damage the fruit's cellular structures due to ice crystal formation, which

*Corresponding author: kehinde.alabi@kwasu.edu.ng; kennyp4all@yahoo.com

degrades nutritional qualities and reduces market value when done conventionally (Alabi *et al*., 2020). Conventional freezing also causes texture degradation and juice loss in pineapple slices (Ramallo and Mascheroni, 2010; Sirijariyawat and Charoenrein, 2012). In addition, conventional freezing methods are both energy-intensive and costly, making them less practical for large-scale industrial applications (Otero *et al.*, 2023; Panayampadan *et al*., 2022). To address these challenges, magnetic field (MF) treatment has emerged as a novel non-thermal preservation technique that reduces ice crystal growth during freezing, thereby protecting fruit microstructures (Alabi *et al.*, 2024b; 2024b; Otero *et al*., 2016; Enzo-Aldoradin *et al.*, 2019b). Alabi *et al*. (2024b) demonstrated that MF significantly reduced freezing times, maintained cellular integrity, and enhanced the quality of mangoes and tomatoes, while also improving industrial efficiency by reducing energy consumption. In another study, Enzo-Aldoradin *et al.* (2019b) found that MF minimized ice crystal size, improve texture, and preserved physical and sensory properties of mango. Panayampadan *et al*. (2022) reported that MF up to 7.02 mT gave optimum freezing characteristics of minimally processed guava. Blueberry fruit frozen under MF of 10 mT had minimum ice crystal of 2489 μm^2 when compared to the control (conventional) group that has ice crystal size of 3749 μm^2, leading to a well preserved microstructure in the treated samples (Tang *et al*., 2020a; 2020b). However, despite these promising results, there is limited research on the application of MF to tropical fruits like pineapples, which possess distinct cell structure. Furthermore, the optimal treatment conditions for MF including field intensity and exposure time remain unclear. Thus, this study aimed to examine the effects of MF intensity and exposure time on the quality characteristics of frozen pineapple slices. The quality characteristics investigated include pH, firmness, total soluble solids and microstructure. It is hoped that the study would provide valuable insights into optimizing MF-enhanced freezing process of pineapple slices for the food industry.

MATERIALS AND METHODS

Materials

The raw material (pineapple) used for the experiment was obtained from a local farm in Malete, and transported to the Laboratory, Department of Food and Agricultural Engineering, Kwara State University (KWASU), Malete, Nigeria. The equipment used for pretreatment was MF device that was locally fabricated at the Department of Food and Agricultural Engineering, (KWASU). Others equipments used are: food grade hand glove, measuring tape, stainless steel knife, stainless bowl, ziplock nylon, stop watch, freezing machine, magnetic field device, pH meter, refractometer, and scanning electron microscopy (SEM).

Experimental Design

The experiment followed a randomized complete block design (RCBD) with two main variables: (1) magnetic field intensity, and (2) exposure time. The study involved two control samples: (1) fresh samples and (2) fresh samples frozen without a magnetic field treatment. Pineapple slices were randomly assigned to treatment groups (MF treatments 1-3) as illustrated in Table 1:

Table 1: Factors and their levels

Factors	Levels		
Magnetic Field Intensity (T)	A1 = 9	A2 = 14	A3 = 20
Exposure Time (min)	B1 = 5	B2 = 10	B3 = 15

MF treatment 1: Pineapple slices exposed to a magnetic field of 9 T, 14 T and 20 T for 5 minutes (Assigned as: A1 B1; A2 B1; A3 B1).
MF treatment 2: Pineapple slices exposed to a magnetic field of 9 T, 14 T and 20 T for 10 minutes (Assigned as: A1 B2; A2 B2; A3 B2).
MF treatment 3: Pineapple slices exposed to a magnetic field of 9 T, 14 T and 20 T for 15 minutes (Assigned as: A1 B3; A2 B3; A3 B3).
Control group 1: Fresh pineapple (A0)
Control group 2: Pineapple slices frozen without magnetic field treatment (B0).

Experimental Procedure

Fresh pineapples (*Ananas comosus*) weighing 5.0 ± 2 kg, were washed with distilled water and cleaned with absorbent paper to remove dirt. The cleaned samples were peeled and sliced into 10 X 10 X 10 mm cubes, as shown in plate 1, in order to maintain uniform field effect during the experiment.

Plate 1: Pineapple sample under slicing operation

Magnetic Field Treatment

The magnetic field treatment was conducted by allowing the sliced samples to pass through magnetic field at: (1) 9 T and exposure time of 5 minutes, (2) 9 T and exposure time of 10 minutes, (3) 9 T and exposure time of 15 minutes, (4) 14 T and exposure time of 5 minutes, (5) 14 T and exposure time of 10 minutes, (6) 14 T and exposure time of 15 minutes, (7) 20 T and exposure time of 5 minutes, (8) 20 T and exposure time of 10 minutes, (9) 20 T and exposure time of 15 minutes. Immediately after the treatments, the treated and untreated samples were subjected to freezing at -18 ^oC.

Freezing

The samples, whether fresh or field treated, were frozen at -18°C for 2880 seconds using a freezing machine (Nexus 010 basic 3 x 380/220 V, 50 Hz, Zurich, Switzerland). After freezing, the samples were stored at -18°C for 15 days in sealed high density polyethylene bags. Thawing was performed at room temperature for 8 hours prior to analysis. Qualities including pH, firmness, TSS and microstructure changes in –all the samples were evaluated using standard methods. The experimental procedure for the magnetic field-assisted freezing of pineapple is given in Figure 1.

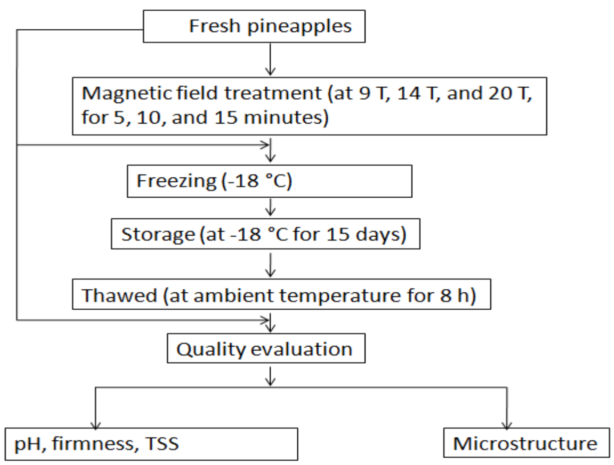


Figure 1: Experimental procedure for the magnetic field-assisted freezing of pineapple

Quality Analysis

pH

A pH meter (pH-3C Hellog, Guangzhou, China) was used to monitor the acidity levels of the pineapple slices, according to AOAC (2000) standard method. It has a range from 0 to 14 pH; covering the full spectrum of possible pH values, with an accuracy of ±0.01.

Firmness

The firmness of fresh, untreated and treated frozen pineapple was assessed following the method of Enzo-Aldoradin *et al.* (2019a) with slight modifications. Firmness was measured using the compression function of a texture analyzer (Brookfield, model CT3-1500, USA) fitted with a flat-ended cylindrical plunger (8 mm diameter) operating at a speed of 0.5 mm/s. The device recorded the maximum firmness (N) corresponding to a penetration depth of 6 mm. To ensure consistent contact between the plunger and the sample surface, the slightly convex layers near the skin were removed. Specifically, approximately 1 mm of pineapple skin was trimmed before analysis.

Total Soluble Solids

The total soluble solids (TSS) values were determined following the method described by Bartz and Brecht (2003). Juice was extracted from the various samples, and a small amount of the juice was placed on a handheld refractometer (HRB32-T, Krüss Optronic Co., Ltd., Germany). The displayed TSS values were then recorded.

Microstructure

Microstructure changes in the pineapple slices were observed using scanning electron microscopy, SEM (Model: JSM-6510LV, JEOL) according to Alabi *et al*. (2023). Prior to SEM analysis, the samples were freeze-dried to preserve their structural integrity and coated with a thin layer of gold. Micrographs were taken at 500x magnifications to examine cellular structure and ice crystal formation.

RESULTS AND DISCUSSION

Effect of Field Intensity and Exposure Time on pH

The pH level is an essential parameter in assessing the quality and stability of frozen and thawed fruit products. In this study, MF treatment prior to freezing significantly impacted the pH stability of pineapple slices. Figure 2 shows the effect of field intensity and exposure time on the pH of the slices. As shown in Figure 2, pineapple slices treated with higher magnetic field intensities (20 T) exhibited more stable pH levels compared to both untreated (B0) samples and those exposed to lower intensities. This stability can be attributed to the reduced cellular damage, as smaller and more uniform ice crystals formed under the magnetic field's influence. Consequently, this reduced the leakage of organic acids and bases from the cell walls during freezing and thawing, thereby maintaining a consistent pH. Extended treatment time (15 minutes) also contributed to improved pH stability. Prolonged exposure to the magnetic field allows for better alignment of water molecules, leading to enhanced control over ice crystal formation, which led to better preservation of cellular integrity. This effect was observed in the reduced pH fluctuations in samples exposed to longer treatment times. These findings indicated that optimizing both magnetic field intensity and exposure time can effectively stabilize the pH of pineapple slices after thawing, which is crucial for maintaining their sensory and nutritional quality. Acidification is often caused by the release of organic acids from damaged cells and tissues observed during conventional freezing of fruits and vegetables (Wang *et al*., 2020). The results were also in agreement with Chen and Wang (2019) who reported that magnetic field-assisted freezing preserves fruit structure, minimizes acidification and maintains a desirable pH level, resulting to well-preserve flavor, color and texture during extended storage.

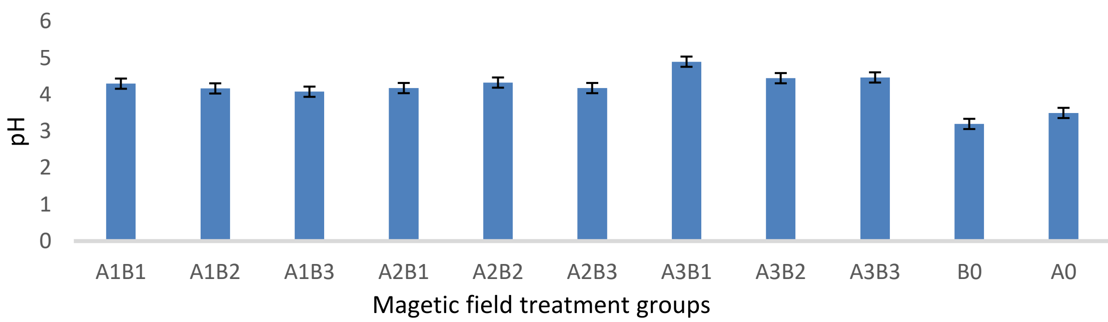


Figure 2: Effect of field intensity and exposure time on pH

Effect of Field Intensity and Exposure Time on Firmness

The firmness or hardness of pineapple slices is a key quality factor that influences consumer perception, as it is closely tied to the structural integrity of the fruit tissue. As shown in Figure 3, treatment with higher magnetic field intensities, especially at 20 T, significantly preserved the firmness of pineapple slices. Moreover, longer exposure time gave enhanced firmness retention. In contrast, MF-untreated samples showed a significant decrease in hardness after thawing, likely due to the formation of larger ice crystals that caused substantial cell damage. This highlights the potential of magnetic field-assisted freezing as an effective method to retain the firmness and fresh-like quality of pineapple slices. The retention of firmness in the MF-treated samples indicated that the magnetic field helps maintain structural integrity during freezing (González-Fandos and Sanz 2017). In agreement with the previous studies, Patel and Reddy (2019) reported that higher magnetic fields stabilize cell membranes during freezing, reduce number of ice crystal formation, leading to improved firmness in pineapple slices.

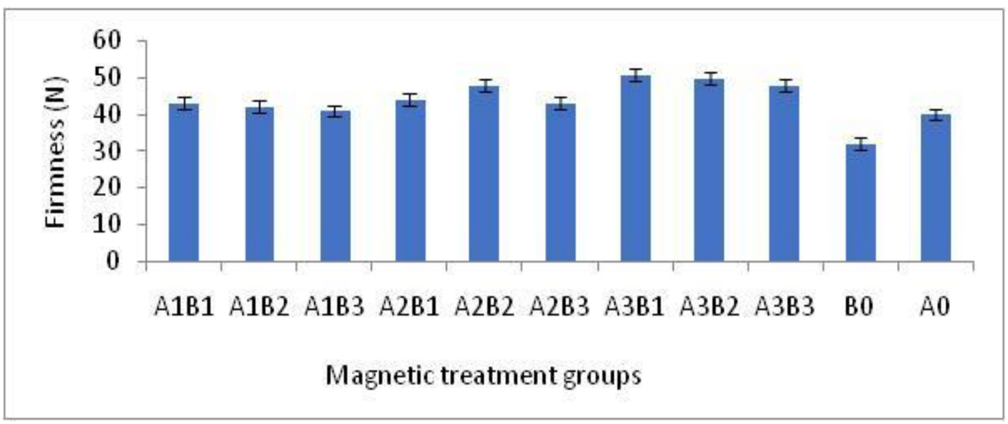


Figure 3: Effect of magnetic field intensity and exposure time on the firmness of pineapple slices

Effect of Field Intensity and Exposure Time on Total Soluble Solids

Total Soluble Solids (TSS) is also a key parameter that measures fruit quality. Figure 4 shows the effect of field intensity and exposure time on the TSS of pineapple slices. As depicted in Figure 4, magnetic field treatment prior to freezing positively enhanced the TSS retention. Samples treated with higher magnetic field intensities gave higher TSS retention, very close to the control 1 (fresh sample), when compared to MF-untreated ones. This observation is as a result of enhanced solutes, rigid cell and less leakage of soluble solid found in the treated samples. The control group 2 exhibited a notable TSS, due to significant cell damage and drip loss during thawing. Although, the differences in TSS retention between MF-treated and untreated samples was not statistically significant, the slices treated with magnetic field showed a tendency toward better preservation of sweetness and flavor; which are quality preferences for consumer acceptance (Jariyawaranugoon, 2015). The findings aligned with the findings of Tang *et al*. (2020b), who demonstrated that magnetic field treatment reduces freezing damage, retaining the natural quality of cherry fruit.

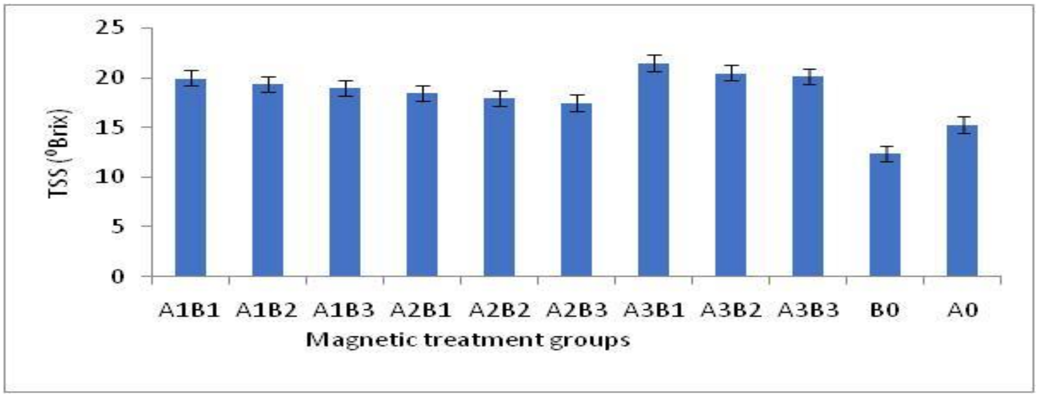


Figure 4: Effect of magnetic field intensity and exposure time on TSS of apple slices

Effect of Field Intensity and Exposure Time on the Microstructure

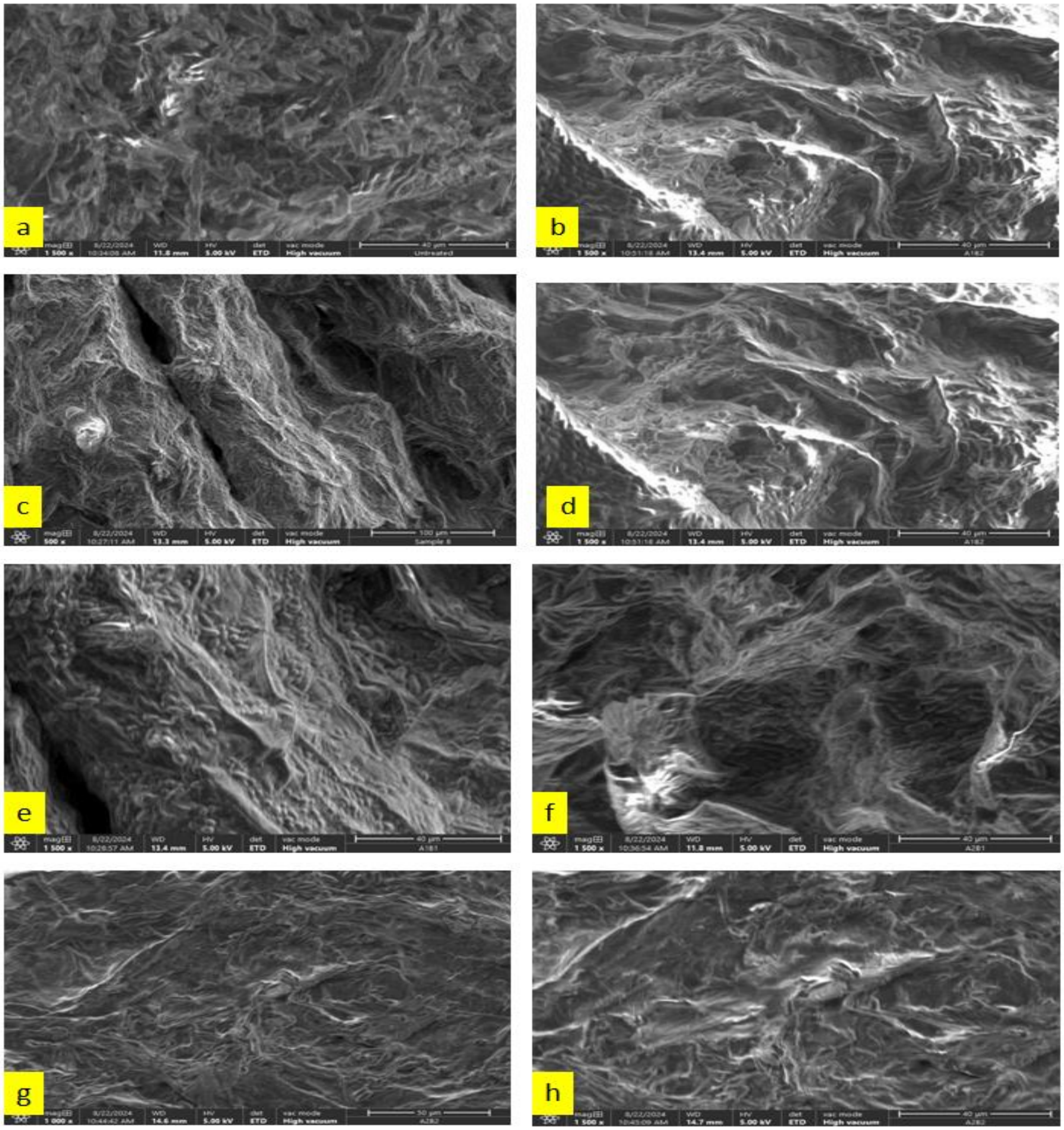
Samples from all treatment groups, along with unfrozen fresh control samples (A0) and conventionally frozen fresh control sample 2 (B0) were analyzed for microstructure changes. Sample A0 showed a well-organized cellular structure with tightly packed cells and intact cell walls. Plate 2 show the effect of field intensity and exposure time on the microstructure of pineapple slices. As shown in plate 2a, the cytoplasm was dense, and there was distinct intercellular space, reflecting the natural state of the fruit tissue. In contrast, the conventionally frozen sample (B0) exhibited structural damage compared to the fresh samples (A0). SEM images revealed large and irregular ice crystals damage to the cell wall (Plate 2b). In plate 2b, the cells appeared shrunken, with a marked loss of turgor, and many signs of rupture. Additionally, the intercellular spaces had elongated a bit when compared to the fresh sample, which indicated large ice crystal formation within the cells, leading to expansion of middle lamella and cell filaments.

The microstructure analysis of the MF-treated samples revealed significant improvements compared to the MF-untreated samples. In all the treated groups (plates 2c –2k), ice crystals were notably smaller and more evenly distributed. This minimized mechanical damage to cell walls, allowing the cells to retain much of their original shape and structure. In the lower MF-treated sample groups A1B1 (plate 2c), A1B2 (plate 2d), and A1B3 (plate 2e), the cytoplasm appeared denser, with reduced intercellular space in comparison to the untreated samples. These groups showed minor cell wall damage but maintained significantly better structural integrity than the MF-untreated groups. The smaller ice crystals contributed to the preservation of cell shape. As for the sample groups A2B1, A2B2, and A2B3 shown in plates 2f, 2g, and 2h respectively, the medium MF-treated samples demonstrated even greater improvements, with cells remaining largely intact and showing minimal signs of rupture. The ice crystals were smaller and more uniformly distributed, indicating enhanced preservation of the cellular structure.

However, sample A3B1, A3B2, and A3B3, being the highest MF-treated samples, produced the best-preserved microstructure, as illustrated in plates 2i to 2k. The cells in these samples exhibited the least damage, with very small and numerous ice crystals uniformly distributed within the sample mass. The overall structure closely resembled that of the fresh sample, indicating that the high-intensity magnetic field treatment is the most effective at maintaining the microstructure integrity of frozen pineapple slices.

Plate 2 shoed the effect of MF intensity and exposure time on microstructure changes of frozen pineapple slices (a) microstructure changes of fresh pineapple (b) microstructure changes of MF-untreated frozen pineapple (c) microstructure changes of pineapples during MF-assisted freezing (at 9 T, 5 mins), (d) microstructure changes of pineapples during MF-assisted freezing (at 9 T, 10 mins), (e) microstructure changes of pineapples during MF-assisted freezing (at 9 T, 15 mins), (f) microstructure changes of pineapples during MF-assisted freezing (at 14 T, 5 mins), (g) microstructure changes of pineapples during MF-assisted freezing (at 14 T, 10 mins), (h) microstructure changes of pineapples during MF-assisted freezing (at 14 T, 15 mins), (i) microstructure changes of pineapples during MF-assisted freezing (at 20 T, 5 mins), (j) microstructure changes of pineapples during MF-assisted freezing (at 20 T, 10 mins), (k) microstructure changes of pineapples during MF-assisted freezing (at 20 T, 15 mins). Scale bar = 100 µm.

These micrographs provide evidence supporting the hypothesis that MF treatment influences ice crystal formation during freezing (Alabi *et al.*, 2024). Alabi *et al*. (2024) reported that magnetic fields played a significant role in the alignment of water molecules, resulting in smaller ice crystals and less damage to cell walls. This effect was most pronounced in the 20 T-treated samples, which showed well-preserved cellular structures. Moreover, the findings aligned with Enzo-Aldoradin *et al*. (2019b), who also reported enhanced microstructure integrity in MF-assisted freezing of mango.


a
b
c
d
e
f
g
h

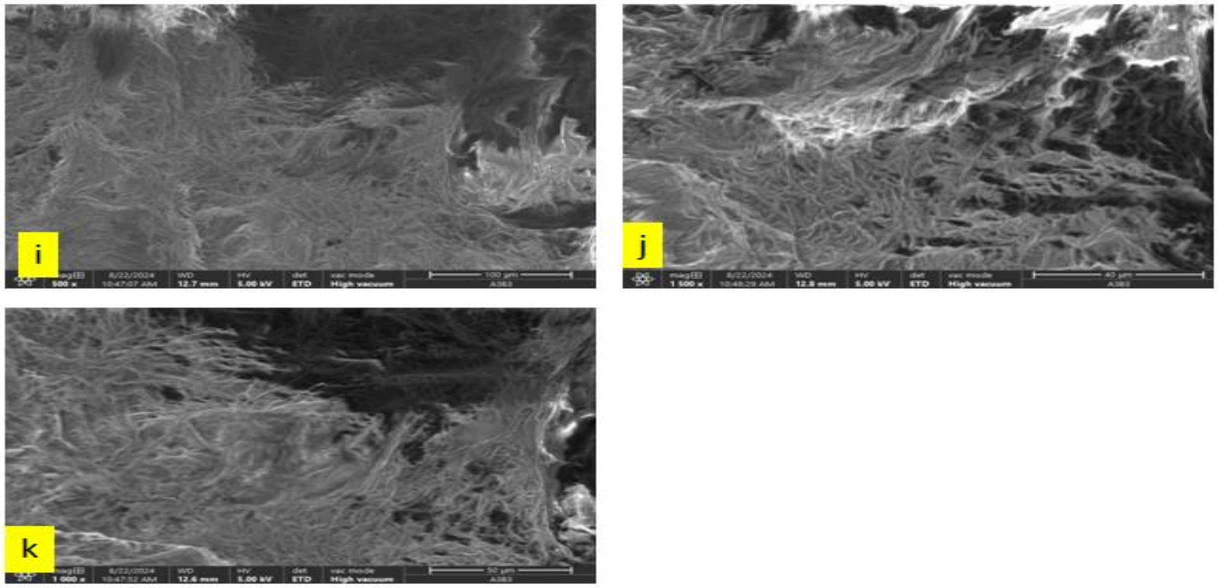


Plate 2: Effect of MF intensity and exposure time

CONCLUSION AND RECOMMENDATION

This study assessed the effect of magnetic field (MF) intensity and exposure time on the quality characteristics of pineapple that were frozen under magnetic field-assisted freezing. The MF treatment has a positive impact on the quality characteristics of frozen pineapple slices, highlighting its potential in the frozen food industry. The MF intensity and exposure time induced only minor changes in the pH levels of the pineapple slices, and produced substantial improvements in firmness, total soluble solids (TSS), and the preservation of microstructure integrity. One of the key mechanisms identified was the reduction in ice crystal formation during freezing, which helped maintain the cellular structure of the pineapple slices. The study recommended MF as a non-thermal processing method for improving the quality of frozen fruits, as it could provide significant advantages to the frozen food industry by enhancing product quality without compromising nutritional value or requiring extensive chemical treatments. Future studies should investigate the applicability of MF treatment to other types of fruits and vegetables to assess its broader potential. Additionally, exploring the effects of MF on long-term storage stability and optimizing thawing processes could provide deeper insights into its practical utility. Understanding the scalability of MF treatment and its cost-effectiveness in industrial settings will also be crucial to its adoption on a commercial scale.

Acknowledgements

The Authors are grateful to the Technical Staff of the Department of Food and Agricultural Engineering, Kwara State University, Malete, Kwara State, Nigeria for their support in acquiring experimental equipment/apparatus.

Author's Contributions

KPA conceived and developed the MF device, carried out the experiment and performed data analysis, KK did the editing while OPO conducted scanning electron microscope analysis. ATO wrote the initial draft, while OAI acquired experimental materials, journals, books, and conference proceedings.

Ethical Statement

Not applicable

REFERENCES

Alabi, K. P., Fadeyibi, A. & Obateru, F. T. (2023). Magnetic Field Hydrocooling System: Effect of Field Intensities on the Cooling Characteristics of Three Different Leavy Vegetables. *Innovative Food Science and Emerging Technologies*, 86:1–8. https://doi.org/10.1016/j.ifset.2023.103347

Alabi, K. P., Olalusi, A. P., Isa, J., and Jaiyeoba, K. F. (2024a). Supercooling Phenomenon of Magnetic Field-Assisted Freezing and Its Impacts on Quality Preservation of Frozen Fruits and Vegetables. *Food Biophysics* 15:1–16. https://doi.org/10.1007/s11483-024-09873-3.

Alabi, K. P., Olalusi, A. P., Isa, J., & Jaiyeoba, K. F. (2024b). Effect of Microcontroller-Based Pulsed Magnetic Pretreatments on Some Quality of Frozen-Thawed Mango and Tomato. *Food and Bioprocess Technology* 12(2):155–164.

AOAC (2000). Official Methods of Analysis of The Association of Official Analytical Chemist. Arlinton, Virginia, USA."

Bartz, J. A. & Brecht, J. K. (2003). Basic Postharvest Physiology of Vegetables. In Jerry A. Bartz and Jerry K.

Brecht (Ed.). Postharvest PhysioIogy and Pathology. New York, Pp. 23–32

Chen, T. & Wang, L. (2019). Magnetic Field Effects on Freezing and Thawing of Plant Tissues. Cryobiology 86:88–95.

Enzo-Aldoradin, P., Esteban, F., Mayo, C., José , M. A., Polo, A. P., De la Matta, J. S., and Espinoza, J. C. A. (2019a). Effect of Freezing with Oscillating Magnetic Fields on the Physical and Sensorial Characteristics of Mango." *Brazilian Journal of Food Technology*, 22:1–11.

Enzo-Aldoradin, P., Dubouchet, J. and Skali-Lami, S. (2019b). Influence of Oscillatory Magnetic Fields on the Microstructure of Frozen-Thawed Mango. *Food Structure*, 22:100–113.

FAO. (2019). Major Tropical Fruits. Statistical Compendium Rome FAO 01:18–21.

González-Fandos, E. & Sanz, S. (2017). Microbiological Safety and Quality Aspects of Frozen Fruits. In Frozen food science and technology (In J. W. Zhang, Z. G. Liu (Eds.). John Wiley & Sons Pp. 251–174.

Jariyawaranugoon, U. (2015). Effect of Freezing on Quality of Osmotically Dehydrated Banana Slices. *Advance Journal of Food Science and Technology*, 9(2):98–105.

Otero, L., Antonio, C., Rodríguez, M. Pérez-Mateos, & Pedro, D. S. (2016). Effects of Magnetic Fields on Freezing: Application to Biological Products. *Comprehensive Reviews in Food Science and Food Safety*, 15(3):646–657. https://doi.org/10.1111/1541-4337.12202.

Otero, L., Antonio, C., Rodríguez, I. M. R. Costo, Patricia De, & Pedro, D. S. (2023). Effect of Oscillating Magnetic Fields on Freezing of a Colloidal Dispersion of Superparamagnetic Nanoparticles. *Journal of Food Engineering*, 347:1–12.

Panayampadan, A. S., Alam, M. S., Aslam, R., Gupta, S. K., & Gagandeep, K. S. (2022). Effects of Alternating Magnetic Field on Freezing of Minimally Processed Guava. *LWT-Food Science and Technology* 163:1–10.

Patel, A. & Reddy, K. (2019). Impact of Freezing on Physicochemical Properties of Fruits. *Food Quality Journal*, 42(2):112–220.

Ramallo, L. A. & Mascheroni, R. H. (2010). Dehydrofreezing of Pineapple. *Journal of Food Engineering*, 99(3):269–275.

Sirijariyawat, A. & Charoenrein, S. (2012). Freezing Characteristics and Texture Variation after Freezing and Thawing of Four Fruit Types. *Songklanakarin Journal of Science and Technology*, 34(5):517–523.

Tang, J., Shao S., & Changqing T. (2020a). Effects of the Magnetic Field on the Freezing Process of Blueberry. *International Journal of Refrigeration*, 113:288–295.

Tang, J., Zhang, H., Changqing, T., & Shao, S. (2020b). Effects of Different Magnetic Fields on the Freezing Parameters of Cherry. *Journal of Food Engineering*, 278:1–7. https://doi.org/10.1016/j.jfoodeng.2020.109949.

Wang, L., Li, D. & Zeng, X. (2020). Preservation of Fruit and Vegetable Quality Using High Magnetic Fields during Freezing. *Journal of Food Science and Technology*, 57(4):1001–1010.

Yahia, E. M., Pablo, García-Solís, & María E. M. C. (2019). Contribution of Fruits and Vegetables to Human Nutrition and Health. Elsevier Inc. Assessed online on 24th April 2024.