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Magnetic field hydrocooling system: Effect of field intensities on the cooling characteristics of three different leavy vegetables

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ABSTRACT

The physiological changes occurring during postharvest of leafy vegetables affect quality. To address this, several cooling technologies that utilize physical fields like magnetic fields (MFs) have been proposed. The application of MFs in the cooling of leafy vegetables however remains a substantial controversy among the food engineers. Therefore, the effectiveness should be clarified by experiments. In the current study, the effect of MFs (at 534.1 mT, 458.0 mT, and 396.8 mT) on hydrocooling process of three different leafy vegetables including jute mallow, fluted pumpkin, and bitter leaf was investigated by using a specially designed hydrocooling system facilitated with magnetic field (also known as magnetic field hydrocooling; MFHC) generated from a Neodymium permanent magnet. The investigation included the comparison of the cooling curves, physiological loss in weight (PLW), microbial loads, and observation of microstructures. Based on the results of the experiment, it was observed that the weak magnetic fields provided significant improvement on the hydrocooling technique as well as the quality of hydrocooled vegetables. The MFHC assisted by Neodymium magnet (at 396.8 mT) provided higher cooling rate (at $P \leq 0.05$) when compared with conventional room cooling, reduced microbial loads significantly from 8.40×10^5 to 5.86×10^5 CFU/ml, 7.03×10^5 to 5.89×10^5 CFU/ml and 6.00×10^5 to 4.0×10^5 CFU/ml (at $P \leq 0.05$) for jute mallow, fluted pumpkin and bitter leaf respectively. In addition, hydrocooling-assisted by magnetic field (at 396.8 mT) is more effective in the preservation of the microstructures. The study indicates that the MFHC technology enhances cooling process and preserves the leafy vegetables, thus pose great potential in the food industry.

Practical applications: Leafy vegetables deteriorate faster after harvest; hence, there is a need to cool them in order to extend their shelf-life. MFHC technique has great potentials in preservation of leaves, with the advantage of minimum quality loss due to reduction in cooling time and microbial activities. Currently, innovative studies have been carried out on the use of MFHC technique to improve the cooling process and achieve better quality preservation. However, the findings presented in this work can provide detail insights on the quality of some leafy vegetables that were cooled by MFHC, and give some guidance for further developments of MFHC technology.

1. Introduction

Leafy vegetables posses high nutritional values and have numerous health benefits including prevention of cancers, coronary artery diseases and cardiovascular dysfunction, leading to increased consumption and production worldwide (Rodriguez-Casado, 2016; Yahia, García-Solís, & Celis, 2019). During harvest in spring, leafy vegetables dehydrate rapidly, and cause chemical and physical changes, leading to tissue softening, pigment loss and off colors (FAO, 2004; Kasso & Bekele, 2018). The quality loss is often caused by physiological changes of respiration and transpiration as affected by alteration in temperature, ethylene, O_2, CO_2 and CO concentration (Bartz & Brecht, 2003). Besides physiological changes, others factors like the microbial activity contributes to the quality reduction of some harvested vegetables (Li, Lichter, Kenigsbuch, & Porat, 2015). In the review of Mostafidi, Reza, and Shirkhan (2020), the activity of microorganisms contributes significantly to the quality reduction and has important safety implications during storage of vegetative tissues. Moreover, field heat allows rapid senescence, and thus promotes deterioration and quality reduction in plant-based materials (DeEll, Vigneault, & Lemerre, 2000; Zainal &

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Ding, 2018). The high loss of vegetables has become a major concern in the food industry, and there is need to remove field heat or slow down senescence processes so as to maintained a high level of quality and provide consumer satisfaction. Therefore, food engineers have become more engaged with cooling methods that could be applied to reduce the temperature of products, enhance stable quality, and ensure good postharvest management. Among numerous cooling methods available, hydrocooling is considered novel, very effective and inexpensive (Chepngeno, Kinyuru, Nenguwo, & Owino, 2015; Ferreira, Silva, Pires, Gaspar, & Nunes, 2018; Ribeiro, Cecon, & Finger, 2018; Shen, Wongmetha, Suan, & Shang, 2012). Hydrocooling technique involves spraying of products with cold water or by immersion in cold water or ice water mixture, increasing shelf-life (Brosnan & Sun, 2001). Recent researches in cooling technology of perishable foods have evidently shown that, prompt hydrocooling of leafy vegetables including lettuce (Tsang, 2014) and broccoli (Kochhar & Kumar, 2015), immediately after harvest, inhibits growth of deterioration-causing microorganisms; reduces enzymatic and respiratory activities, thus promoting extended shelf-life. Ribeiro et al. (2018) reported that hydrocooling can significantly remove field heat from iceberg lettuce within 10 min when submerged in cool water at 4 °C and delayed the wilting of external leaves in three and two days when stored at 5 and 22 °C, respectively. Hydrocooling also proved to be a faster technique for cooling minimally processed spinach in spring, decreased respiration rate, and enhanced quality when compared to other cooling methods like conventional room cooling, forced-air cooling and vacuum cooling (Garrido, Tudela, & Gil, 2015). One limitation of hydrocooling is that, if the water contains fungi or bacteria, this can provide them an ideal environment to grow, adding to the microbial loads of fresh vegetables.

Moreover, the increase in global population and the outbreak of COVID-19 pandemic have put treats to food security worldwide. The social distance observed during the pandemic made the vegetable farms farther away from fresh market. Handling and consequent deteriorations lead to severe quality loss and widespread increases in global food insecurity, affecting vulnerable households in almost every country. These situations demand improvement and optimization of appropriate preservation technology that is affordable and sustainable.

Several non-thermal physical field techniques such as electric field, magnetic fields (MFs), ultrasound and electromagnetic fields have been applied to promote long time preservation of vegetables (Alabi, Zhu, & Da-W, 2020; Rodríguez, Otero, Cobos, & Sanz, 2019). Typically, MFs have been widely applied to freezing of cellular foods (Kaur & Kumar, 2019; Rodríguez et al., 2019). To the best of our knowledge, this physical field technique has not been applied to hydrocooling method.

Interestingly, water is diamagnetic, which implies when it is placed in MFs, a magnetic dipole moment is induced in the direction opposite to the applied field, and cause a strong inter-molecule hydrogen bonds, changing specific properties such as viscosity, surface tension and thermal conductivity, thereby increasing cooling efficiency (Aleksandrov, Barannikov, & Dobritsa, 2000; Dalvi-isfahan, Hamdami, Xanthakis, & Le-bail, 2017). However; due to no heating effects, permanent magnet is considered most effective to produce MFs when compared with electromagnet (Kaur & Kumar, 2019). Hence, there is a need to evaluate the effect of the MFs intensities, as generated by permanent magnet, on the efficiency and quality of cooled leafy vegetables. The objective of this work was to determine the effect of magnetic field intensities on the cooling rate, physiological loss in weight (PLW), microbial loads and microstructure of jute mallow, fluted pumpkin and bitter leaf that were cooled by MFHC technique.

2. Materials and methods

Jute mallow '*Corchorus Olitorius*', fluted pumpkin 'Belfairia Occidentalis', and bitter leaf 'Vernonia Amygdalina' were harvested from the field at Kwara State University Malete (KWASU), Nigeria (51° 27′ 49.144″ N 19° 13′ 4.303″ E) in the morning between 8 and 9 am. The leaves were taken to the Laboratory, Department of Food and Agricultural Engineering, KWASU, while dirty leaves with brown spot were removed. MFHC was performed by allowing the mixture of tap water and finely crushed ice at proportion of 4:1 (v:v) to pass through Neodymium magnet with intensity of 534.1 mT, 458.0 mT, 396.8 mT, in a cooling chamber. Because of its 4 unpaired electrons in its electron structure, neodymium magnet has a large magnetic dipole moment that is capable of generating magnetic fields. The strength of neodymium magnets is as a result of several factors including number of magnets, size of magnets, and microcrystalline grain sizes.Fig. 1 shows the arrangement of the magnet, and the magnetic field intensities were generated based on the number of magnets and were measured using a handheld Testla meter. The constructed cooling chamber (14 cm height, 16 cm wide x 32 cm length box) was covered with jute sack to protect it from excessive dehydration. The relative humidity inside the box was 85–90%. Fig. 2 shows the experimental set-up and successive stages of the MFHC system. The leafy vegetables with uniform weight of 40 ± 1 g were subjected to the following treatments: (1) MFHC for 10 min cooling time followed by cold storage at 4 °C for 24 h; (2) conventional (control) room cooling for 10 min cooling time followed by cold storage at 4 °C for 24 h. The temperature of the samples was measured at every 1 min using a digital thermometer, and the procedure was repeated until the temperature dropped to 4 ± 1 °C. The temperatures of the leafy vegetables before initiating the MFHC treatment were between 28 and 30 °C. At the end of MFHC process, the leafy vegetables were removed from the cooling chamber and allowed to drain for 2 min in the air before subjecting them to cold storage at 4 °C for 24 h. (See Figs. 3 and 4.)

2.1. Cooling rate

The cooling rate was calculated by dividing each temperature data point by its corresponding time point, using Eq. (1).

$$\frac{\Delta T}{\Delta t}\ Cooling\ rate\ (^{\circ}C/sec) = \frac{\Delta T}{\Delta t} \tag{1}$$

Where ΔT = change in temperature (°C).
Δt = change in time (*sec*)

2.2. Physiological loss in weight (PLW)

The PLW was measured on an initial weight bases. The initial weight of the samples was measured before cooling and after cooling treatments. The samples were weighed using a sensible weighing balance (PA4101 Ohaus Corp. Pine Brook, NJ USA). PLW was calculated using standard method in AOAC (2000) expressed in Eq. (2).

$$PLW\ (\%) = \frac{Initial\ weight - Final\ weight}{Initial\ weight}\ x\ 100 \tag{2}$$

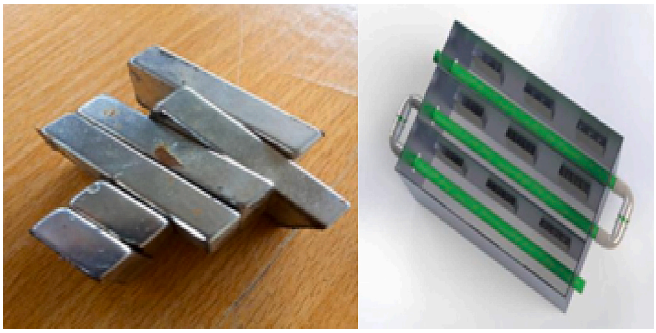


Fig. 1. Neodymium magnets arrangement.

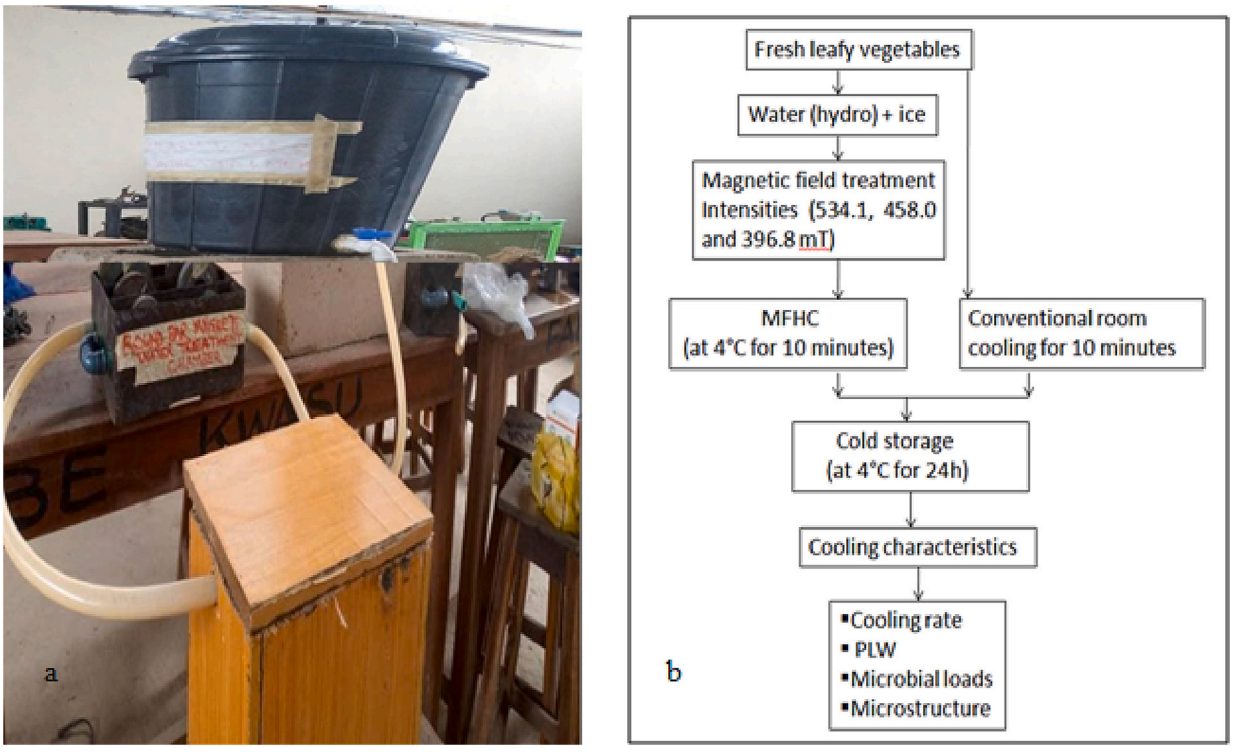


Fig. 2. Experimental set-up and successive stages of the MFHC system (a) experimental set-up of the MFHC system, and (b) successive stages of the MFHC system

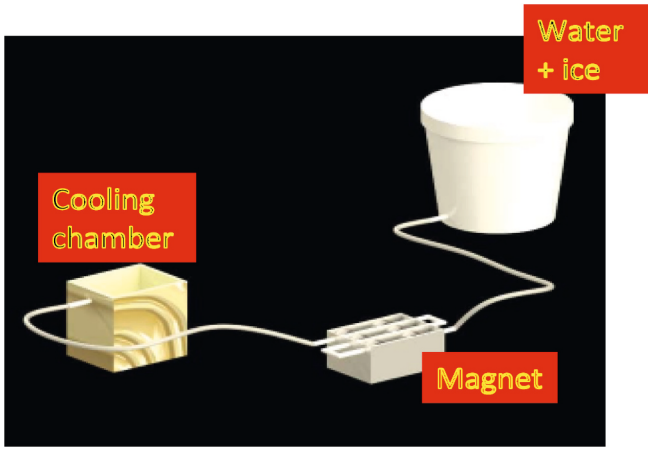


Fig. 3. The 3D view of the MFHC technology.

2.3. Microbial loads analysis

Microbial loads analysis was conducted by using viable plate count method. In order to determine the total mesophilic growth in the samples, bacterial (*E. coli*) cell was cultured and spread on an agar plate (Difco; Becton, Dickinson and Co., Sparks, MD). The plate was incubated at 35 °C for 24 h. Specimens for the total viable counts were prepared first by sterilization of all equipments including nutrient Agar at 121 °C for 15 min. Serial (sequentially) dilutions of the bacterial culture were performed by using a sterile pipette, 9 ml of distilled water and 10 test tubes. However, 1 ml of each specimen was pipette into a culture of the *E. coli* broth and transferred into the first test tube and mixed. From the first test tube, another 1 ml is being transferred into the second test tube and mixed. Afterwards, 1 ml was transferred from the second test tube into the third test tube, and the process was continuously repeated up to the tenth test tube where the nutrient agar was evenly spread over the surface of the plate using a sterile disposal spreader, and put inside an incubator for 24 h. Each sample was processed for microbiological analysis in the same manner as described above.

2.4. Microstructure analysis

Scanning electron microscope (SEM) studies were performed on the surface of the leafy vegetables subjected to MFHC to determine the effectiveness of MFHC on morphological changes in the leaves. The leaves without MFHC treatment were served as controls. The SEM method utilized in this study was based on methods of Kockro et al. (2000) with slight modifications. MFHC and control samples were analyzed at 500 μm to investigate whether or not MFHC preserved the microstructures of the leaves. Samples for SEM were prepared for the hydrocooling environment, and the specimens (approximately 4 mm^2) were cut and fixed with glutaraldehyde in 0.1 M sodium phosphate buffer (pH 7.2) for 24 h. Afterwards, the samples were dehydrated by sequential exposure to ethanol concentrations ranging from 30% to 100% in 10 min. After dehydration, samples were briefly rinsed with distilled water to remove any artifacts and then dried with CO_2 and mounted on aluminum stubs. The specimens were then coated with gold in an ion SEM sputter coater for 2 min, and examined with a Philips PSEM 500 scanning electron microscope.

2.5. Statistical analysis

All measurements taken from the experiments were analyzed in terms of effect of magnetic fields on the cooling efficiency and quality of cooled jute mallow, fluted pumpkin and bitter leaf. The MFs intensities were selected as fixed factors. The cooling efficiency and quality studied including cooling rate, PLW, microbial loads, and microstructure were regarded as response variables. One-way analysis of variance (ANOVA) was employed using SPSS (IBM 21) statistical package, and the significance was set at the level of 0.05.



Fig. 4. Fresh leafy vegetables: (a) Jute mallow (b) Fluted pumpkin (c) Bitter leaf.

3. Results and discussion

3.1. Cooling rate

The temperature evolutions in all conventional room cooled samples are apparently the same and slower than the samples treated under MFs. The MFs effectively improved hydrocooling of the leafy vegetables under study. Fig. 5 shows the temperature curves of jute mallow, fluted pumpkin, and bitter leaf respectively, during the MFHC process. The curves indicated that the temperature of Bitter leaf and Fluted pumpkin dropped faster than jute mallow in all treatments, which is due to a large surface area and internal air spacing of the bitter leaf and fluted pumpkin respectively. However, the temperatures evolution in the samples were slightly different because of structural heterogeneity, variation in composition and intercellular space (Alabi et al., 2020). For instance, jute mallow showed a slower temperature drop, in all the treatments, because of the small size and shape of the product. Normally, heat can transfer faster in foods with a large surface area, and numerous stomata for evaporation (Zhu, Geng, & Sun, 2020). The MFHC allows water migration across the stomata, the migration potential weakened with increasing distance in the leaf surfaces, resulting in faster cooling rates and lower temperatures being observed in the Bitter leaf and Fluted pumpkin.

As shown in Fig. 5, lowering the temperature reduction rates could significantly increase the total cooling time ($p \leq 0.05$). The increase in the time to change the temperature from initial value (ambient) to final value (4 °C) was linear with the cooling time up to 8 min. However, as the temperature rates continuously decreased, the relationship was no longer linear since the gradual increase in cooling time did not significantly decrease the temperature, but held slightly at 4 °C for all treatments.

The influence of MFHC on the temperature reduction varies among the field intensities. At the magnetic field intensity of 534.1 mT, the temperature of the treated samples dropped to the final cooling value of 4 °C at exactly 8 min, while the temperature of the untreated samples dropped to 14 °C, indicating that the MFHC is a fast cooling technique. The average temperature change rates of the leafy vegetables at different magnetic field intensities at 534.1 mT, 458.0 mT and 396.8 mT during MFHC were 2.3, 2.4, 2.8 °C/min, 2.4, 2.5, 2.8 °C/min, and 2.6, 2.8, 3.1 °C/min for jute mallow, fluted pumpkin and bitter leaf respectively. After reaching the final cooling value of 4 °C, the temperatures of the vegetables were much more constant.

3.2. Physiological loss in weight (PLW)

The PLW of magnetic field hydrocooled leafy vegetables was not significantly affected by different levels of magnetic field intensities. Table 1 show the Duncan multiple range test (DMRT) of the effect of the MFHC on the PLW of cooled vegetables. The result indicated the MFHC has no meaningful loss in physiological weight loss (0.40–0.62%) among the treated and untreated samples. The findings was in agreement with DeEll et al. (2000), who reported no significant difference in weight loss (4.9–6.9%) between the hydrocooled and non-treated cucumber. Zainal & Ding, (2018) reported significant effect on weight loss during days of storage of hydrocooled rockmelon fruits. Their findings showed increased trend of weight loss, by 1.40, 1.68 and 2.15% for storage period of 1, 2, and 3 days respectively.

3.3. Microbial loads

The MFHC technology reduced the microbial loads of the three vegetables significantly. As shown in Table 2, the total viable count of the bacterial cells was reduced from 8.40×10^5, 7.03×10^5, 6.00×10^5(CFU/ml), to 5.86×10^5, 5.89×10^5, 4.0×10^5 (CFU/ml) for jute mallow, fluted pumpkin and bitter leaf respectively. Moreover, the experiment shows that the low magnetic field intensity produced by the

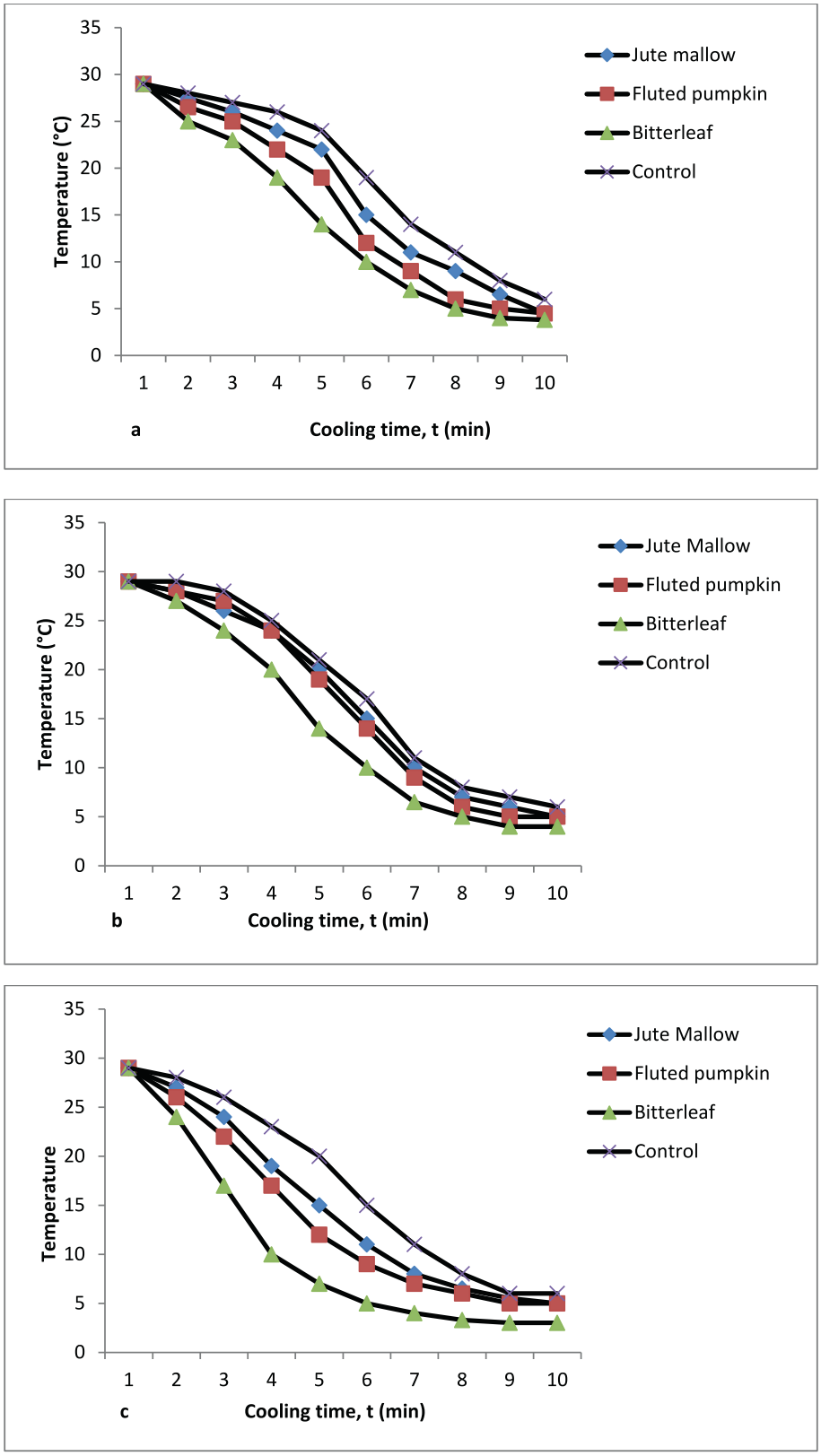


Fig. 5. Variations in the temperature and time during magnetic fields hydrocooling of leafy vegetables (a) cooled at 534.1 mT (b) cooled at 458.0 mT and (c) cooled at 396.8 mT.

Table 1
Duncan multiple range test (DMRT) of the effect of MFHC on the PWL of hydrocooled leafy vegetables.*

Treatments		PWL (%)		
		Jute mallow	Fluted pumpkin	Bitter leaf
Field intensities	Control	0.61 ± 03^{a}	0.70 ± 01^{a}	0.62 ± 02^{a}
	534.1 mT	0.51 ± 03^{b}	0.52 ± 01^{c}	0.46 ± 02^{d}
	458.0 mT	0.50 ± 03^{b}	0.51 ± 01^{c}	$0.52 \pm 02^{b,c}$
	396.8 mT	0.62 ± 03^{a}	0.69 ± 01^{a}	0.61 ± 02^{a}

* Samples with the same superscript are not significantly different.

Table 2
Duncan multiple range test (DMRT) of the effect of MFHC at different field intensities on microbial loads of leafy vegetables.*

Treatments		Microbial loads count x 10^{5}(CFU/ml)		
		Jute mallow	Fluted pumpkin	Bitter leaf
Field intensities	Control	8.40 ± 02^{a}	7.03 ± 02^{a}	6.00 ± 03^{a}
	534.1 mT	5.86 ± 02^{c}	5.90 ± 02^{c}	4.50 ± 03^{c}
	458.0 mT	6.30 ± 02^{c}	5.89 ± 02^{c}	4.40 ± 03^{c}
	396.8 mT	8.33 ± 02^{a}	6.96 ± 02^{b}	5.92 ± 03^{a}

* Samples with the same superscript are not significantly different.

permanent magnet can achieve a better effect in killing food pathogens and will be a novel direction of the development of food equipments (Mingdan, Jun, Yong, Pengfei, & Sifen, 2013).

3.4. Microstructure observation

A sequential arrangement of plant tissues at microscopic level is one of the essential way to plant transpiration, and it is also a basic channel for heat transfer during the cooling process (Alabi et al., 2020). The microstructure changes, according to the untreated (conventional room cooling) and MFHC (at 396.8 mT) of jute mallow, fluted pumpkin and bitter leaf, are shown in Fig. 6, Fig. 7 and Fig. 8, respectively. The Figures show well preserved microstructures for samples cooled using MFHC technique as compared with the (control) samples cooled under conventional room cooling. The microscopic analysis indicated an evolution of heat in the cooled matrix, leading to minimum cell damage, which can be attributed to the high cooling rate obtained under MFHC operated at 396.8 mT. On the other hand, conventional room cooling resulted in small opening of the vegetative tissues, which hindered heat transfer, causing damages to the cell walls. The damages to the cell walls are shown by the arrows in the micrographs. However, the findings in the present study is in agreement with the results of Zainal, Ding, Ismail, and Saari (2019) who reported intact microstructure of hydrocooled rockmelon in comparison with non-hydrocooled ones. Therefore, magnetic fields hydrocooling was found to have a positive effect on microstructures where it application has maintained cell wall structure of the leafy vegetables after harvest.

4. Conclusion

The use of physical fields like MFs in conjunction with hydrocooling (known as magnetic hydrocooling; MFHC) can help to avoid postharvest problems associated with freshly cut leafy vegetables. Static MFs can be generated from Neodymium magnets and can significantly improve vegetables hydrocooling efficiency by changing the structure of water and its physicochemical properties. Therefore, we investigated the effect of static MFs at three different magnetic field intensities (534.1 mT, 458.0 mT, and 396.8 mT), compared with conventional (control) room cooling, during hydrocooling process of three different vegetables including jute mallow, fluted pumpkin, and bitter leaf. The parameters studied include cooling rate, physiological loss in weight, microbial loads and microstructures. The magnetic fields assisted-hydrocooling shows no meaningful weight loss, increases the cooling rate and reduces microbial loads of the cooled leaves under study. Moreover, scanning electron microscope images confirmed that the morphological changes in the microstructures of the magnetic hydrocooled (at 396.8 mT) vegetables were associated with intact cell wall when compared with the ones cooled under conventional room cooling. In conclusion, MFHC technique can significantly improve hydrocooling process, reduce microbial loads and preserve microstructure of jute mallow, fluted pumpkin, and bitter leaf, enhancing their postharvest quality. Thus, open doors for application of MFs in the preservation of some other food materials. For a correct interpretation of the data, future research should consider different range of induced fields during the hydrocooling experiments and its potential consequences, particularly during storage.

Author contributions

Kehinde Peter Alabi conceptualized, perform the experiment and

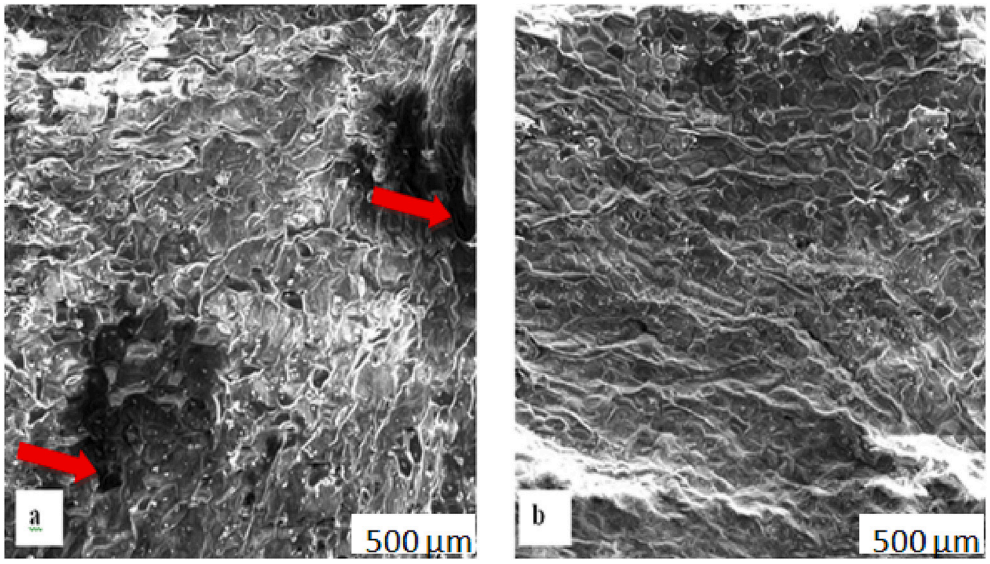


Fig. 6. Effect of MFHC on morphological changes of jute mallow (a) morphological changes of jute marrow during conventional room cooling (b) morphological changes of jute marrow during MFHC (at 396.8 mT). Scale bar = 500 µm.

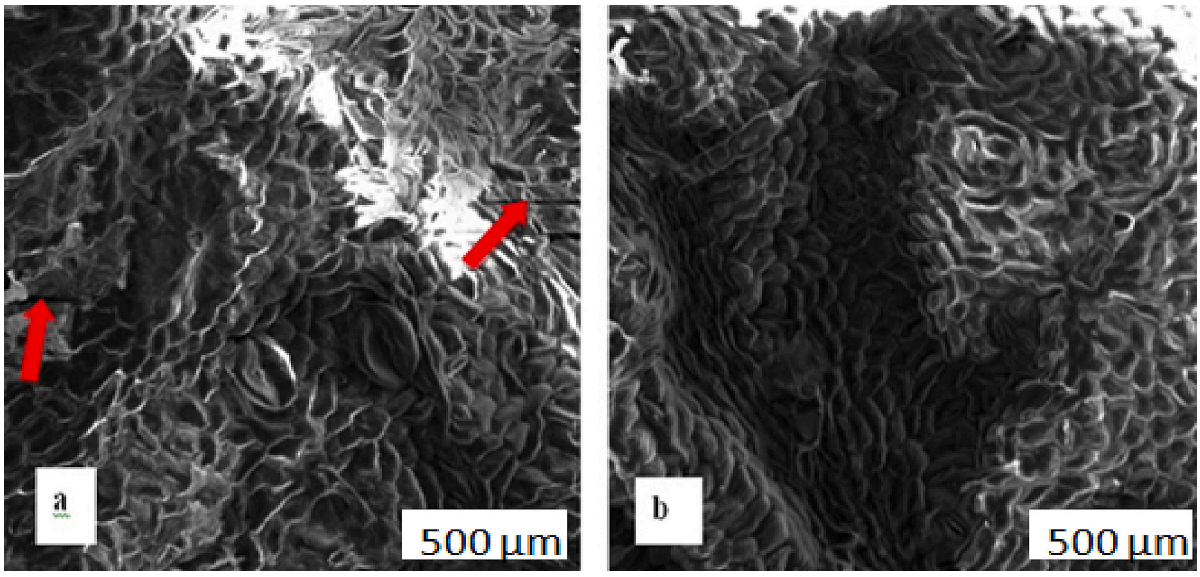


Fig. 7. Effect of MFHC on morphological changes of fluted pumpkin (a) morphological changes of fluted pumpkin during conventional room cooling (b) morphological changes of fluted pumpkin during MFHC (at 396.8 mT). Scale bar = 500 µm.

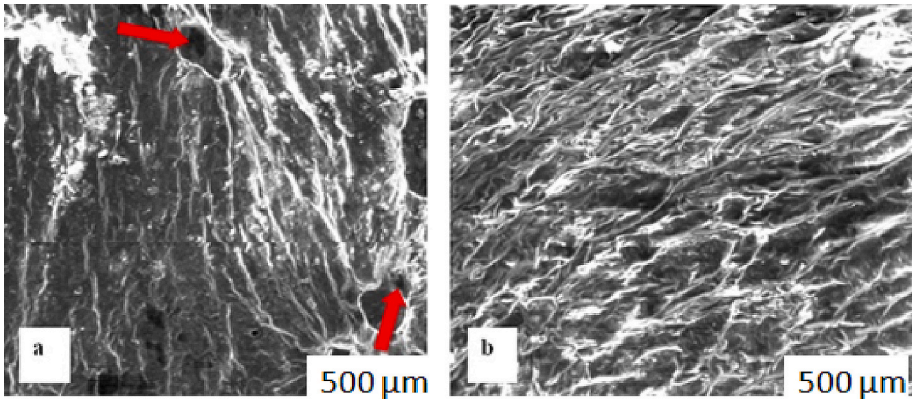


Fig. 8. Effect of MFHC on morphological changes of bitter leaf (a) morphological changes of bitter leaf during conventional room cooling (b) morphological changes of bitter leaf during MFHC (at 396.8 mT). Scale bar = 500 µm.

conducted data analysis, writing- original draft, and editing. Adeshina Fadeyibi conducted formal analysis including Figures and Tables while Faith Tinuade Obateru performed journals, books, and conference proceedings acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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