BRAZILIAN JOURNAL OF FOOD TECHNOLOGY

ISSN 1981-6723
Online version

ORIGINAL ARTICLE

Evaluation of traditional freezing and electromagnetic field-assisted freezing in the physical and sensory properties of avocado (*Persea americana* Mill) variety Hass

Avaliação do congelamento tradicional e do congelamento assistido por campo eletromagnético nas propriedades físicas e sensoriais do abacate (*Persea americana* Mill) *variedade Hass*

Enzo Aldoradin-Puza[1]*, Cynthia Rodríguez-Mázmela[2], Frank Esteban Cuba-Mayo[3], Cindy Victoria Morán-González[2], José Miguel Alemán-Polo[1]

[1]Colegio de Ingenieros del Perú, San Isidro/Lima – Perú
[2]Instituto Tecnológico de la Producción (ITP), CITE Agroindustrial Chavimochic, La Libertad – Perú
[3]Instituto Tecnológico de la Producción (ITP), CITE Pesquero Callao, Callao – Perú

***Corresponding Author:** Enzo Aldoradin-Puza, Colegio de Ingenieros del Perú (CIP), Street: Guillermo Marconi, 210, San Isidro/Lima - Peru, e-mail: enzo_499@hotmail.com

Cite as: Aldoradin-Puza, E., Rodríguez-Mázmela, C., Cuba-Mayo, F. E., Morán-González, C. V., & Alemán-Polo, J. M. (2022). Evaluation of traditional freezing and electromagnetic field-assisted freezing in the physical and sensory properties of avocado (*Persea americana* Mill) variety Hass. *Brazilian Journal of Food Technology*, *25*, e2021083. https://doi.org/10.1590/1981-6723.08321

Abstract

This study evaluated the effect on physical and sensory properties of freezing Halved Avocados (HA) by Traditional Method (TM) in a continuous freezer and by electromagnetic field-assisted method (EM) with CAS (Cells Alive System) freezer, obtaining HATM and HAEM, respectively. Each HA from the same specimen (obtaining 2 HA: one for fresh and the other for frozen-thawed state) was coded and evaluated. The firmness of the upper part of the fresh HA was higher ($p < 0.05$) than the lower part. The freezing curve showed the crystallization phase in the HAEM (from 14.25 to 20.33 min), thus indicating the formation of ice crystals, as well as affecting the significant decrease ($p < 0.05$) in more than 60% of firmness in the thawed HA concerning the fresh state. Regarding the color, there were differences ($p < 0.05$) in saturation (C*) between fresh and thawed avocado (HATM and HAEM); however, there were no differences ($p > 0.05$) in the tonality (h*). Weight loss of thawed HA was less than 0.5%. The sensory evaluation indicated there were no significant differences ($p < 0.05$) in firmness between the HATM and HAEM using the triangular test.

Keywords: Avocado; Traditional freezing; Electromagnetic field-assisted freezing; Firmness.

Resumo

Este estudo avaliou o efeito nas propriedades físicas e sensoriais do congelamento de abacates cortados ao meio (AH) pelo método tradicional (MT) em freezer contínuo e pelo método assistido por campo eletromagnético (EM) em um freezer CAS -Cells Alive System, obtendo HATM e HAEM, respectivamente. Cada HA do mesmo espécime (obtendo 2 HA:

um para o estado fresco e outro para o estado congelado-descongelado) foi codificado e avaliado. A firmeza da parte superior do AH fresco foi maior (p < 0,05) do que a parte inferior. A curva de congelamento mostrou a fase de cristalização no HAEM (de 14,25 a 20,33 min), indicando a formação de cristais de gelo, afetando a diminuição significativa (p < 0,05) em mais de 60% da firmeza do HA descongelado em relação ao estado fresco. Quanto à cor, houve diferença (p < 0,05) na saturação (C*) entre abacate fresco e descongelado (HATM e HAEM); porém, não houve diferenças (p > 0,05) na tonalidade (h*). A perda de peso do HA descongelado foi inferior a 0,5%. A avaliação sensorial indicou que não há diferenças significativas (p < 0,05) na firmeza entre o HATM e o HAEM pelo teste triangular.

Palavras-chave: Abacate; Congelamento tradicional; Congelamento assistido por campo eletromagnético; Firmeza.

1 Introduction

The Hass variety avocado (*Persea americana* Mill) is a highly appreciated climacteric fruit in the world, where Mexico is the main exporter, followed by Peru (Ministerio de Agricultura y Riego, 2019). In Peru, during 2018, fresh avocado represented 90% of the exports of this product; however, there is a progressive increase in exports of frozen avocado (Gestión, 2019).

Freezing in foods describes a change in the state that occurs in 3 successive stages: i) pre-cooling (temperature of the fruit when it enters the freezer); ii) crystallization phase; and iii) cooling (until reaching a temperature lower than -18 °C). However, freezing forms ice crystals during the crystallization phase, where at a slower freezing speed larger ice crystal are formed, and this crystal negatively affects firmness and generates exudate, which is perceived in thawed fruits and vegetables (Alvarez & Canet, 1997). To minimize surface darkening in frozen fruit such as avocados, pre-treatment such as food additives (citric acid and ascorbic acid) and blanching are applied (Bower & Dennison, 2003; Soliva et al., 2000).

To minimize these defects, novel freezing techniques have been developed to include the use of electric fields (Xanthakis et al., 2013), microwaves (Xanthakis et al., 2013), high pressure (Otero et al., 2000), and Electromagnetic Fields (EM) (Owada, 2007). In this regard, only EMs have been implemented at the industrial commercial level (Rodríguez et al., 2019). ABI Corporation (Chiba, Japan) markets electromagnetic field-assisted freezing, known as a CAS (Cells Alive System) freezer. The CAS freezer consists of a conventional rapid freezing system together with a low-frequency electromagnetic wave system, where the EM is divided into a static magnetic field (it does not change the intensity or direction independent of the alternating current) and an oscillating magnetic field (it varies with time and rotates azimuthally around the center of the magnetic field) (Owada, 2007). Owada (2007) indicates that thawed foods (which were frozen by the CAS freezer) maintain sensory characteristics similar to their fresh state. In this regard, it does not mention or restrict what types of foods, implying that it can be applied to all foods in general. Likewise, Kaur & Kumar (2020) have carried out a literary review and argue the advantages of the application of assisted freezing with magnetic fields in fruits and vegetables.

Experimental studies have been carried out using the CAS freezer. The quality of thawed foods such as mackerel muscle (Okuda et al., 2020), cherry (Tang et al., 2020), mango cubes (Puza et al., 2019), crab sticks (Otero et al., 2017), garlic bulbs (James et al., 2015), chicken breasts (Yamamoto et al., 2005) were evaluated and compared to traditional freezing, however not all studies did not report considerable advantages for CAS freezing. For CAS freezing, some advantages were reported concerning parameters (time) of the freezing process, but the decrease in firmness also occurs in traditional freezing. However, so far, there is no reliable report that indicates a comparative advantage of CAS freezing with respect to traditional freezing, since results cannot be compared with each other and reproduced as the number of experiments performed was not sufficient to be statistically significant to obtain valid conclusions (Rodríguez et al., 2019), since food may have different firmness with respect to their structure. Firmness is one of the main sensory attributes required by the consumer when tasting fruits (Bianchi et al., 2016), where sensory (subjective) and instrumental (objective) methods are used to assess firmness.

This study aimed to compare the effect of freezing by traditional method (HATM) and the freezing assisted with EMs (HAEM) in the physical and sensory characteristics of the Hass variety avocado (*P. americana*), where the avocado was presented in halved avocado (HA), in which one half was evaluated in the fresh state and the other half was evaluated in the thawed state.

2 Material and methods

2.1 Raw material

Whole Hass variety "*Persea americana*" avocado (n = 200) was used in the ripened state (net weight: 240-360 g, total length: 10-12 cm, thickness: 6.7-8.3 cm) of extra category (Codex Alimentarius, 1995), harvested in the second half of 2018 in the La Libertad Region (Peru). All the avocado specimens were without peduncle, since the presence of the peduncle delays the ripening of the fruit (Tochihuitl-Martiñón et al., 2018).

2.2 Conventional industrial processing and freezing

In La Libertad, avocados (n = 90) were processed in an agro-export company that consisted of: i) reception; ii) blanched (90 °C for 20 s); iii) cooled (7 °C) and disinfected in sodium hypochlorite solution (100 mg L^{-1}) for 2 min; iv) longitudinally cut and pitted; v) removal of the edible part (mesocarp), obtaining 2 halved avocados (HA); vi) immersion in anti-browning solution (7 °C, 1 min ; pH: 1.53 ± 0.15) (whose composition is reserved); vii) drained of HA, and then individually arranged for freezing in a continuous air blast freezer (-35 °C for 30 min). Then, these HA were considered as frozen HA by the traditional method (HATM).

A random part of the HATM (n = 40) and the whole avocados (n = 110) were duly sent in isothermal boxes by land in less than 24 h to the Technological Institute of Production (*Instituto Tecnológico de la Producción* (ITP)) (Callao) (HATM arrived at 1 °C and were placed in refrigeration for evaluation within 4 h).

2.3 Processing and freezing assisted with electromagnetic fields

At ITP, the whole avocados (n = 110) were processed following the guidelines indicated above and frozen (-30 °C for 60 min) in an electromagnetic wave-assisted freezer (Model CAS-30B, ABI Corporation Ltd., Chiba, Japan).

The CAS freezer was a static blast freezer that consists of a forced-air freezer (with 2 fans) that had a built-in system of weak Oscillating Magnetic Fields (OMF) and Static Magnetic Fields (SMF). This equipment had a control panel, where process parameters are programmed: i) cooling temperature; ii) ventilation speed during cooling (50% cooling FAN equivalent to 1.9 m/s (Otero et al., 2017)); iii) CAS freezing temperature; iv) ventilation rate (programmed to 50% CAS FAN equivalent to 1.9 m/s (Otero et al., 2017)) during CAS freezing; v) CAS energy; and vi) freezing time. Puza et al. (2019) could describe the most important description of dimensions, number of trays, among others. Likewise, measurements of OMF were reported by Otero et al. (2017), who indicated variations in OMF (less than 1 mT) inside the CAS freezer and a maximum of 60 Hz for 100% CAS energy.

HA (n = 30) samples were arranged individually on 2 trays (N° 5 and 6), according to the numbering determined by Otero et al. (2017), and were frozen at each CAS energy as following: 0, 50, 75, and 100%. Freezing at 0% CAS energy was considered the "control" group which is like the traditional method since freezing was carried out without activating the OMF in the control panel. These samples were named HA frozen by EMs method (HAEM) and to eliminate the effect of freezing storage, these samples were placed in polyethylene bags and evaluated the next day (kept refrigerated at 3 °C overnight).

2.4 Freezing curve

Before the freezing operation, the CAS freezer was cooled to -30 °C for at least 1.5 h. In general, the upper part of the HA presented greater area and volume than the lower part (Figure 1). Thus, the tip of a thermistor (Data Tracer®, type MPIII, model 7500T, USA) was inserted approximately in the center geometry of the upper part of each HA (n = 4) located in tray No. 5, to measure the temperature of the thermal center during the freezing process.

The temperature of the freezing curve was recorded at a resolution of 0.001 °C at intervals of 30 s for 60 min of total time determined by preliminary tests (data not shown). Likewise, the air temperature of each %CAS energy was recorded with 2 thermistors, where the air temperature dropped to -30 °C within the first 5 min, and subsequently remained between -28 and -31 °C (data not shown).

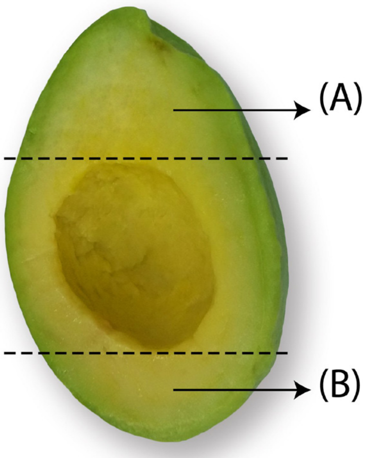

Figure 1. Upper part (A) and lower part (B) of the halved avocado (HA).

2.5 Firmness

Since the firmness of fruit varies between the specimens of the same lot, to compare the change in firmness between the fresh and the thawed avocado, 2 HA were obtained by a longitudinal cut of the same avocado and they were coded: i) one half was evaluated in fresh state and ii) the other half was frozen and evaluated in the thawed state. This coding was carried out on the avocado specimens processed in the ITP, since this coding was not carried out in the agro-export company due to the continuous high production work.

To measure the firmness, frozen HA of each %CAS energy was thawed by putting them under refrigeration (3 °C) overnight, then at room temperature (25 °C) for 30 min (to reach about 7 °C in their thermal center). Later, each thawed HA was half cut (see dotted lines in Figure 1), obtaining an upper part and a lower part (Figure 1), close to the peduncle and base of the avocado, respectively. Fresh HA was also half cut in the same way (Figure 1).

According to Puza et al. (2019), the firmness of the upper and lower part of each HA was measured by a texturometer (Brookfield, model CT3-1500, USA).

2.6 Weight loss

For each CAS energy (%), HA (n = 5) was weighed in the fresh and thawed state (with previous drying using absorbent paper) to determine the weight loss, expressed as the percentage of decrease in weight of HA, due to the loss of fluids after thawing. Weight loss was calculated according to Equation 1:

$$Weight\ loss\ (\%) = \frac{(Pf - Pt)}{Pt} \times 100 \quad (1)$$

Where Pf and Pt correspond to the weight of fresh and thawed HA, respectively.

2.7 Color

Regarding this analysis, only the yellow part of the avocado was measured, since in this part, the color change visibly occurs in a fresh avocado during browning (figure not shown). Thus, the color of the HA (n = 3), previously ground, was measured with a colorimeter (Nippon Denshoku ZE-200, Japan) in CIELAB color scale, where: i) L*: luminosity (0 to 100); ii) a*: from red (+) to green (-); iii) b*: from yellow (+) to blue (-), iv) C*: chromaticity or color intensity, v) h*: hue angle or color tone, and vi) ΔE: total color difference. The total color difference (ΔE) of each thawed HA (HATM and HAEM) was compared to fresh HA.

C*, h* and ΔE were calculated according to Equations 2, 3, and 4, respectively.

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (2)$$

$$h^* = tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (3)$$

$$\Delta E^* = \sqrt{(\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)^2} \quad (4)$$

2.8 pH

The pH was determined in a mixture (10%) of HA crushed and diluted with deionized water and read directly by an electrode (Sensorex) coupled to a potentiometer (Mettler Toledo, model S20K Seven Easy, USA).

2.9 Sensory evaluation

The sensory evaluation was performed on thawed HA, which has been frozen by the traditional method (HATM) and by EMs method (HAEM) of each CAS energy (0, 50, 75, and 100%). The triangular test was used (Norma Técnica Peruana, 2010). This test was carried out by 9 trained panelists who were asked to identify the different samples in relation to their firmness or bite force. Thus, 4 panelists randomly received: 2 HATM samples and 1 HAEM sample, and the other 5 panelists received: 2 HAEM samples and 1 HATM sample. In order that triangular test can be statistically significant, at least 6 panelists must correctly identify the different sample for a significance level of $\alpha = 0.05$ (Norma Técnica Peruana, 2010).

This sensory evaluation was not carried out between the fresh and thawed HA (HATM and HAEM), since the difference between both states was noticeable, and easy to identify the different samples in relation to its firmness. In all cases, the fresh HA presented, when chewing, notably greater firmness than both HATM and HAEM.

2.10 Analysis of data

The statistical program SPSS (version 18) (IBM Corp., NY, USA) was used. The normality of the fresh HA firmness data (upper and lower) was evaluated using the Shapiro-Wilk Test and its comparison of medians using the Mann-Whitney Test. The normality of the results of the freezing parameters, change in firmness, and the color was evaluated by the Shapiro-Wilk test, then the one-way Analysis of Variance (ANOVA) was evaluated, followed by the evaluation of comparison of multiple means by Duncan's Test. A level of significance of $p = 0.05$ was established.

3 Results and discussions

3.1 Raw material

The firmness of ripened and fresh avocado in HA presentation is shown in Figure 2. The firmness frequency distribution was obtained according to the Sturges Rule (Machado et al., 2010). The upper part had 6 intervals and 1.56 N of interval width, while the lower part had 6 intervals and 1.28 N of interval width.

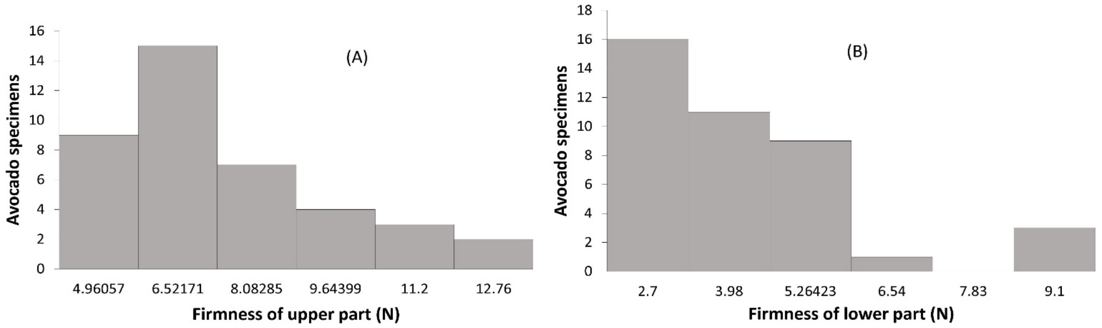

Figure 2. Frequency distribution of firmness of upper part (A) and lower part (B) of the fresh HA (n = 40).

The firmness data of all the fresh HA (upper and lower part) did not present a normal distribution ($p < 0.05$) according to the Shapiro Wilk Test, therefore, the Mann-Whitney Test (as a non-parametric test) was used for the comparison of medians, indicating that the firmness of the upper part (6.47 N) was significantly higher ($p < 0.05$) than the lower part (3.52 N) (Figure 3).

Owing that firmness varied moderately between each avocado specimen, we decided to record the firmness of each HA of each avocado (2 HA was obtained from 1 avocado) to compare the change in firmness of one HA in the fresh state and the other HA in the thawed state. Regarding the upper part of the avocado in the fresh state, the lower part presented less firmness, probably because the base of the fruit (lower part) ripens faster, as happens in pineapples (Food and Agriculture Organization of the United Nations, 2000); this can also be explained in the study made by Tochihuitl-Martiñón et al. (2018) who reported greater firmness of avocado with the presence of peduncle compared to avocado without the presence of peduncle during 14 days of storage, therefore, the presence of the peduncle in avocado provides phytohormones such as auxin that inhibits or delays fruit ripening (Tingwa & Young, 1975), and this could develop with greater incidence in the upper part that is closer to the peduncle. Thus, the firmness of the upper part of the avocado is significantly greater than the lower part as reported instrumentally (through a texturometer) in this study.

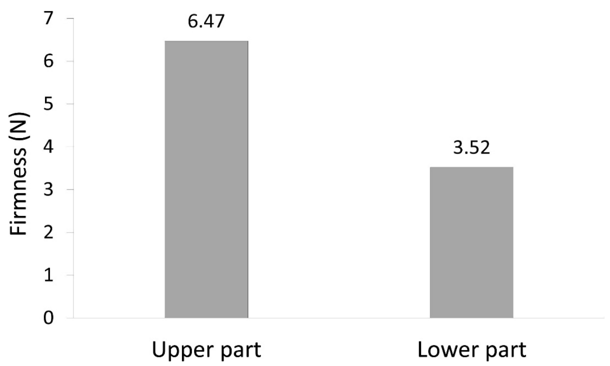

Figure 3. Firmness (expressed as the median) of the upper and lower part of the fresh HA.

3.2 Freezing curve

Table 1 indicates the freezing parameters at different CAS energy applied in HA at -30 °C. The 3 freezing stages, pre-cooling, crystallization phase, and tempering, occurred at all programmed CAS energy. The total freezing time for the HA was from 42.68 to 47.00 min, obtaining a freezing speed from 0.77 to 0.85 °C min^{-1}, in both cases, since there were no significant differences ($p > 0.05$). On the other hand, there were significant differences ($p < 0.05$) in the time and speed of the crystallization phase, ranging from 14.25 to 20.33 min and 0.20 to 0.28 °C min^{-1}, respectively.

Table 1. Freezing parameters (mean ± SD) of HA in the CAS freezer at -30 °C (n = 4).

Parameters	CAS energy*			
	0%	50%	75%	100%
Complete freezing (from +18 °C to -18 °C)				
Time (min)	45.67 ± 2.05^a	42.68 ± 2.49^a	47.00 ± 3.74^a	47.00 ± 3.74^a
Speed (°C min^{-1})	0.79 ± 0.04^a	0.85 ± 0.05^a	0.77 ± 0.06^a	0.77 ± 0.06^a
Crystallization phase (from -1°C to -5°C)				
Time (min)	14.25 ± 1.71^a	14.50 ± 1.29^a	19.00 ± 1.63^b	20.33 ± 1.04^b
Speed (°C min^{-1})	0.28 ± 0.04^b	0.28 ± 0.02^b	0.21 ± 0.02^a	0.20 ± 0.01^a

*Different superscript letters in the same row indicates significant difference between means ($p < 0.05$).

As it happens in traditional freezing, Tang et al. (2020), Okuda et al. (2020), and Otero et al. (2017) also reported the appearance of the 3 freezing stages when freezer-assisted with magnetic fields were employed in cherry, mackerel, and crab sticks, respectively. Likewise, it is known that to minimize the deterioration of food quality it is required that the crystallization phase occurs in the shortest possible time (Hartel, 2002), since if this step was longer, larger ice crystals can be formed. These crystals would break to a greater extent toward the cell walls (plant tissue such as fruits) and cell membranes (animal tissue) affecting mainly the food firmness which is evidenced when thawed. Even though HA frozen with 0 and 50% CAS energy had a shorter time ($p < 0.05$) in the crystallization phase (Table 1), firmness decreased noticeably in all the samples frozen with or without CAS energy (Figure 4), thus indicating that the size of ice crystals generated during CAS freezing was of the same size as those formed during traditional freezing.

Ice crystals formed during freezing, (predominantly in the crystallization phase) cause deterioration in the firmness quality of thawed foods. This deterioration can be determined on the same day or on the next day of freezing in vegetable matrices (present study) and in a few weeks for animal matrices (Okuda et al., 2020; Yamamoto et al., 2005). Unlike animal tissue, plant tissue is more prone to quality deterioration during freezing because their cells are semi-rigid when fresh, but weak and easily broken when water change to large ice crystals (Otero et al., 2000). Therefore, the freezing in fruits can break the cell wall and rapidly affect the firmness or turgor of the fruit, being evident even on the same day of freezing (Puza et al., 2019).

3.3 HA firmness

Figure 4 shows the firmness (expressed as a percentage) of the thawed HA (upper and lower part) compared to its fresh state, where the firmness of the HA in the fresh state represented 100% as initial firmness. The firmness of all thawed HA (upper and lower part) presented a normal distribution ($p > 0.05$) according to the Shapiro-Wilk Test in all applied energy CAS (except the firmness of the lower part of 0% CAS that presented a p-value equal to 0.003).

In all CAS energy (0, 50, 75 and 100%) applied, the firmness of the upper and lower part of the HA decreased in the thawed state compared to its fresh state. The upper part of all thawed HA maintained firmness from 26.10

to 35.01% with respect to its fresh state, i.e., from the fresh avocado (upper part) there was a decrease of more than 65% in firmness after freezing. A similar situation occurred in the lower part of the avocado, which maintained firmness from 28.38 to 37.75% compared to its fresh state, therefore, there was a decrease of more than 62% in firmness after freezing. However, the depth (mm), where the maximum firmness was recorded, was greater in the thawed state (around 40 to 70%) compared to the fresh state (data not shown). Such increase in depth after freezing was also recorded by Puza et al. (2019) on mango cube samples.

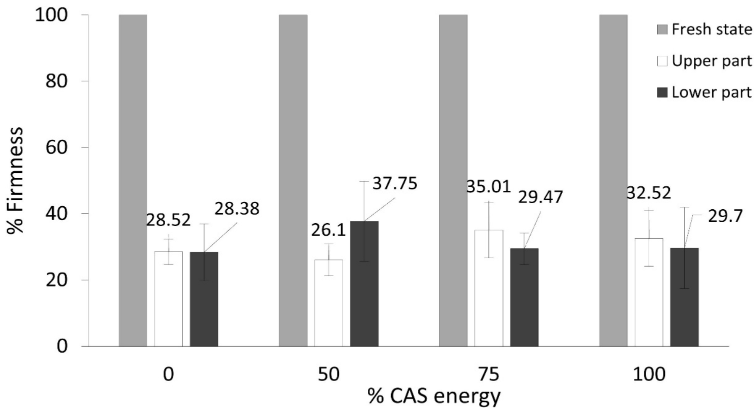

Figure 4. Change of firmness (expressed in %) of the thawed HAEM (upper part and lower part) (n = 10) compared to its fresh state.

Therefore, the firmness of HA in the fresh state was 6.47 and 3.52 N for the upper and lower part, respectively (see Figure 3). The results of fresh HA (expressed as a percentage) were significantly higher compared to all thawed states of HAEM (explained by Figure 4).

The HA frozen at 0% CAS decreased by more than 70% in its firmness with respect to its fresh state (Figure 4). In this regard, we could not measure the decrease in firmness (in percentage) from fresh to the thawed state of the HA processed in the agro-export company by traditional freezing due to its mass production area condition; however, we can infer that both the traditional freezing and electromagnetic wave-assisted freezing had the same effect in decreasing the firmness in HA, according to the results indicated in Table 2.

Table 2. Firmness (N) (n = 10) of thawed HA (upper and lower part) that were frozen by traditional freezing and by freezing assisted with electromagnetic fields.

Freezing Type	Firmness (N) of thawed HA*	
	Upper part	Lower part
Traditional freezing	2.76 ± 0.86^{c}	$1.54 \pm 0.60^{a,b}$
0% CAS	1.60 ± 0.25^{a}	1.05 ± 0.60^{a}
50% CAS	$1.92 \pm 0.70^{a,b}$	1.16 ± 0.38^{a}
75% CAS	$2.41 \pm 0.71^{b,c}$	1.11 ± 0.39^{a}
100% CAS	3.02 ± 1.28^{c}	2.04 ± 1.24^{b}

*Different superscript letters in the same column indicate significant differences between means ($p < 0.05$).

According to Table 2, all the firmness of thawed HA (upper and lower part) presented a normal distribution ($p > 0.05$) according to Shapiro-Wilk Test (except the firmness of the frozen upper HA with 75% CAS, which presented a p-value of 0.030). Respect to the firmness of fresh HA (6.47 N for upper part and 3.52 N for lower part, see Figure 3), a noticeable decrease in the firmness of the thawed HA (top and bottom) was recorded either when frozen by the traditional method or by the CAS system, both presented low firmness values from 1.60 to 3.02 N of the upper part and from 1.05 to 2.04 N from the lower part, showing slightly significant differences ($p < 0.05$) between them.

The significant decrease in firmness in avocado reported in the present study (using CAS freezing), was also evidenced in mango, which presented a decrease from 63% to 77% in firmness for 0% and 100% CAS energy, respectively (Puza et al., 2019); likewise, in apple and potato they presented a decrease in firmness of around 54% and 46%, respectively, under conditions of 0%, 25%, 50%, 75% and 100% CAS energy (Purnell et al., 2017).

3.4 Color

Table 3 indicates the color parameters of the yellow part of the HA in a fresh and thawed state. In general, there were slightly significant differences ($p < 0.05$) in luminosity and value of "a" that even share similarities (seen by the superscripts) between fresh and thawed states. On the other hand, there were moderate significant differences ($p < 0.05$) in the values of "b" and chromaticity (C*) that differentiate fresh from thawed HA. Likewise, the tonality (h*) did not present significant differences ($p > 0.05$) between all the samples evaluated, indicating that all the HA had a tone very close to yellow and starting with green (90° strictly indicates a yellow tone).

It is worth mentioning that due to the negative value of "a" and positive value of "b", it was corrected by adding 180° to the value of h* (Lancaster et al., 1997), since in the CIELAB scale, the value of these parameters ("a" negative on the abscissa and "b" positive on the ordinate) is located in the second quadrant of a cartesian plane, which after applying the formula of Equation 3, the resulting angle is in radians, which then has to be converted in sexagesimal degrees (the CIELAB color system is represented by a sphere from 0 to 360° according to Euclidean geometry) (Gonnet, 2001). In this study, the results were around -83° for the hue angle (Equation 3); however, 180° had to be added to this result to return to the second quadrant and thus interpret the value of the tonality (around 95°, see Table 3) that corresponds between the yellow and green tone, but closer to yellow, which is precisely the portion of the sample evaluated.

Table 3. Fresh and thawed HA color parameters (mean ± SD) (n = 3).

Halved avocado (HA)	Color parameters**					
	L*	a*	b*	C*	h*	ΔE
Fresh	73.91 ± 0.93^{b}	-3.44 ± 0.56^{b}	36.55 ± 0.73^{a}	36.72 ± 0.70^{a}	95.39 ± 0.94^{a}	0
HATM	71.43 ± 1.80^{a}	-5.25 ± 0.94^{a}	43.59 ± 2.91^{b}	43.91 ± 2.81^{b}	96.92 ± 1.60^{a}	7.88 ± 2.85
0% CAS	$71.77 \pm 0.94^{a,b}$	$-3.80 \pm 0.92^{a,b}$	43.71 ± 4.10^{b}	43.88 ± 4.11^{b}	94.98 ± 1.15^{a}	7.55 ± 4.20
50% CAS	$71.84 \pm 1.04^{a,b}$	$-3.95 \pm 0.83^{a,b}$	43.28 ± 3.06^{b}	43.46 ± 3.07^{b}	95.22 ± 1.04^{a}	7.16 ± 2.73
75% CAS	71.59 ± 1.21^{a}	$-3.76 \pm 0.75^{a,b}$	43.95 ± 3.53^{b}	44.11 ± 3.53^{b}	94.91 ± 0.95^{a}	7.84 ± 3.82
100% CAS	$72.20 \pm 0.72^{a,b}$	$-4.02 \pm 0.59^{a,b}$	43.78 ± 2.18^{b}	43.96 ± 2.22^{b}	95.23 ± 0.53^{a}	7.48 ± 1.93

**Different superscript letters in the same column indicate significant differences between means ($p < 0.05$).

Likewise, the total color difference (ΔE) between each thawed HA with respect to the fresh HA was less than 8 in all cases (Table 3), which according to Gonnet (1999), constitutes as "small differences" perceptible when the ΔE is less than 10; that is, the freezing of the HA (HATM and HAEM) did not cause major color changes (based on L*, a* and b*) in the evaluated samples. Results showed that there was a difference between the color (L*, a*, b* and C*) of fresh and all frozen-thawed samples, but no difference was found between the method of freezing or CAS setting.

3.5 Weight loss

Weight loss of the thawed HA from HATM and HAEM is indicated in Table 4. For all cases, the thawed HA did not visibly present an exudate, thus, they did not present perceptible fluids or liquids that come from the same HA after thawing; whereas the small differences in weight may be mainly due to the minimum amount of water adhered to the paper that was used to dry before weighing the thawed HA. For this reason, an exudate of less than 0.5% (equivalent to 0.5 g weight loss for around 120 g of fresh HA) was considered for all HA from HAEM. On the other hand, the initial weight of HA in its fresh state was not available (this should have been registered in the agro-export plant), however, these HATM did not have weight loss when thawed, so the same value of weight loss (less than 0.5%) like PMMCE was considered.

Table 4. Thawed HA weight loss (HAEM and HATM) (n = 5).

HA	% Weight loss
0% CAS	< 0.5
50% CAS	< 0.5
75% CAS	< 0.5
100% CAS	< 0.5
HATM	< 0.5*

*Assumed by observation in a thawed state.

On the other hand, after freezing fruits with electromagnetic wave assistance, the weight loss in thawed mango (Puza et al., 2019), cherries (Tang et al., 2020), and apple and potato (Purnell et al., 2017) were reported to be 4%, from 4.79 to 6.67% and from -2.4% to -4.2%, respectively. With respect to that, the low weight loss (around 0.5%) that occurred in thawed avocado in our study could be probably because those fruits (of the other studies) are composed mainly of water, carbohydrates, and a minimum content of fat (less than 0.5%); and other reasons might be the difference in tissue structure among these fruits and the higher fat content of 12.5% in avocado (Reyes et al., 2017).

The occurrence of the crystallization phase (Table 1) in avocado indicates the formation of ice crystals and possibly the rupture of the cell wall of the fruit, evidenced by a notable decrease in its firmness in thawed avocados (Figure 4), even so, no external fluids were observed in the thawed HA. Therefore, these fluids could probably be retained by nature and composition (fat or other) of the fruit mesocarp. According to our results, freezing does not provoke loss weight in avocado as happens in other fruits and vegetables, as was discussed previously. Since there are not many published data on frozen avocados, it is useful to state that freezing may cause changes to the color and texture of avocados, however, there is no evidence that it results in any exudate problems unlike many other fruits and vegetables.

3.6 pH

Values of pH of fresh avocado, HATM, and HAEM (for all CAS energy applied) was 6.79 ± 0.21, 5.52 ± 0.21, and 5.87 ± 0.22, respectively. Regarding the fresh avocado, the notable decrease in the pH of the HATM and HAEM occurred since the fresh HA was immersed in a cold anti-frizz solution (pH: 1.53) during its processing before any freezing method, to avoid enzymatic browning (Soliva et al., 2000).

3.7 Sensory evaluation

Table 5 indicates the results of the sensory evaluation of firmness using the triangular test, where the thawed HATM and HAEM were compared. Table 5 indicates that 2 triangular tests, in which HATM compared with 0 and 75% CAS energy were not significant ($p > 0.05$), the panelists could not identify the different sample, where all samples were similar in firmness. On the other hand, the other 2 tests, in which HATM compared with 50% and 100% CAS energy were significant ($p < 0.05$), the panelists could identify the different sample. However, in all cases the panelists did not indicate if the sample identified as different was firmer in respect to the other samples presented.

Table 5. Sensory evaluation of firmness using the triangular test of thawed HA.

Comparison of HATM with HAEM	Panelists (n)	Panelists: With correct answer (n)	Panelists: With wrong answer (n)	Result
0%	9	5	4	Not significant
50%	9	6	3	Significant
75%	9	4	5	Not significant
100%	9	7	2	Significant

4 Conclusion

In the fresh state, the firmness of upper part of the HA was higher than the lower part. The decrease in firmness in frozen HA (HATM and HAEM) can be explained by the formation of ice crystals that could damage and provoke the rupture of cell walls. Freezing also caused changes in the color of avocado but did not cause any noticeable exudate on thawing. Overall, it may be inferred not many advantages in CAS freezing of avocados in comparison to commercially conventionally frozen avocados.

References

Alvarez, M. D., & Canet, W. (1997). Effect of pre-colling and freezing rate on mechanical strength of potato tissues (cv Monalisa) at freezing temperatures. *Zeitschrift für Lebensmitteluntersuchung und -Forschung A*, *205*(4), 282-289. http://dx.doi.org/10.1007/s002170050166

Bianchi, T., Guerrero, L., Gratacós-Cubarsí, M., Claret, A., Argyris, J., García-Mas, J., & Hortós, M. (2016). Textural properties of different melon (*Cucumis melo* L.) fruit types: Sensory and physical-chemical evaluation. *Scientia Horticulturae*, *201*, 46-56. http://dx.doi.org/10.1016/j.scienta.2016.01.028

Bower, J. P., & Dennison, M. T. (2003). Progress in the development of avocado products. *South African Avocado Grower´s Association Yearbook*, *26*, 35-37.

Codex Alimentarius – CODEX. (1995). *Norma del CODEX para el aguacate* (CODEX STAN 197-1995). Rome: CODEX.

Food and Agriculture Organization of the United Nations – FAO. (2000). *Manual de manejo postcosecha de frutas tropicales (papaya, piña, plátano, cítricos)*. Rome: FAO.

Gestión. (2019). Retrieved in 2020, October 6, from https://gestion.pe/economia/venta-palta-peruana-exterior-llego-us-800-millones-2018-260468-noticia/?ref=gesr

Gonnet, J. F. (1999). Colour effects of co-pigmentation of anthocyanin revisited-2. A colorimetric look at the solutions of cyanin co-pigmented by rutin using the CIELAB scale. *Food Chemistry*, *66*(3), 387-394. http://dx.doi.org/10.1016/S0308-8146(99)00088-6

Gonnet, J. F. (2001). Colour effects of co-pigmentation of anthocyanin revisited-3. A further description using CIELAB differences and assessment of matched colours using the CMC model. *Food Chemistry*, *75*(4), 473-485. http://dx.doi.org/10.1016/S0308-8146(01)00221-7

Hartel, R. W. (2002). Crystallization in foods. In A. S. Myerson (Ed.), *Handbook of industrial crystallization* (2nd ed., Chap. 13, pp. 287-304). Oxford: Butterworth-Heinemann. http://dx.doi.org/10.1016/B978-075067012-8/50015-X

James, C., Reitz, B., & James, S. J. (2015). The freezing characteristics of garlic bulbs (*Allium sativum* L.) frozen conventionally or with the assistance of an oscillating weak magnetic field. *Food and Bioprocess Technology*, *8*(3), 702-708. http://dx.doi.org/10.1007/s11947-014-1438-z

Kaur, M., & Kumar, M. (2020). An innovation in magnetic field assisted freezing of perishable fruits and vegetables: A review. *Food Reviews International*, *36*(8), 761-780. http://dx.doi.org/10.1080/87559129.2019.1683746

Lancaster, J. E., Lister, C. E., Reay, P. F., & Triggs, C. M. (1997). Influence of pigment composition on skin color in a wide range of fruit and vegetables. *Journal of the American Society for Horticultural Science*, *122*(4), 594-598. http://dx.doi.org/10.21273/JASHS.122.4.594

Machado, S. A., Nascimento, R. G. M., Miguel, E. P., Téo, S. J., & Augustynczik, A. L. D. (2010). Distribution of total height, transverse area and individual volume for *Araucaria angustifolia* (Bert.) O. Kuntze. *Cerne*, *16*(1), 12-21. http://dx.doi.org/10.1590/S0104-77602010000100002

Ministerio de Agricultura y Riego – MINAGRI. (2019). *La situación del mercado internacional de la palta*. Lima: MINAGRI.

Norma Técnica Peruana – NTP. (2010). *NTP-ISO 4120. Análisis sensorial. Metodología. Prueba triangular*. Lima: NTP.

Okuda, K., Kawauchi, A., & Yomogida, K. (2020). Quality improvements to mackerel (*Scomber japonicus*) muscle tissue frozen using a rapid freezer with the weak oscillating magnetic fields. *Cryobiology*, *95*, 130-137. PMid:32479751. http://dx.doi.org/10.1016/j.cryobiol.2020.05.005

Otero, L., Martino, M., Zaritzky, N., Solas, M., & Sanz, P. D. (2000). Preservation of microstructure in peach and mango during high-pressure-shift freezing. *Journal of Food Science*, *65*(3), 466-470. http://dx.doi.org/10.1111/j.1365-2621.2000.tb16029.x

Otero, L., Pérez-Mateos, M., Rodríguez, A. C., & Sanz, P. D. (2017). Electromagnetic freezing: effects of weak oscillating magnetic fields on crab sticks. *Journal of Food Engineering*, *200*, 87-94, 94. http://dx.doi.org/10.1016/j.jfoodeng.2016.12.018

Owada, N. (2007). US Patent 7237400 B2. Washington, DC: U.S. Patent and Trademark Office.

Purnell, G., James, C., & James, S. (2017). The effects of applying oscillating magnetic fields during the freezing of apple and potato. *Food and Bioprocess Technology*, *10*(12), 2113-2122. http://dx.doi.org/10.1007/s11947-017-1983-3

Puza, E. A., Mayo, F. E. C., Polo, J. M. A., Matta, A. P., Espinoza, J. S., & Alva, J. C. (2019). Effect of freezing with oscillating magnetic fields on the physical and sensorial characteristics of mango (*Mangifera indica* L. cv. “Kent”). *Brazilian Journal of Food Technology*, *22*, e2018169. http://dx.doi.org/10.1590/1981-6723.16918

Reyes, M., Gómez-Sánchez, I., & Espinoza, C. (2017). *Tablas peruanas de composición de alimentos* (10th ed.). Lima: MINSA/INS.

Rodríguez, A. C., Otero, L., Cobos, J. A., & Sanz, P. D. (2019). Electromagnetic freezing in a widespread frequency range of alternating magnetic fields. *Food Engineering Reviews*, *11*(2), 93-103. http://dx.doi.org/10.1007/s12393-019-09190-3

Soliva, R. C., Elez, P., Sebastián, M., & Martín, O. (2000). Evaluation of browning effect on avocado purée preserved by combined methods. *Innovative Food Science & Emerging Technologies*, *1*(4), 261-268. http://dx.doi.org/10.1016/S1466-8564(00)00033-3

Tang, J., Zhang, H., Tian, C., & Shao, S. (2020). Effects of different magnetic fields on the freezing parameters of cherry. *Journal of Food Engineering*, *278*, 109949. http://dx.doi.org/10.1016/j.jfoodeng.2020.109949

Tingwa, P. O., & Young, R. E. (1975). Studies on the inhibition of ripening in attached avocado (*Persea Americana* Mill.) fruits. *Journal of the American Society for Horticultural Science*, *100*(5), 447-449. http://dx.doi.org/10.21273/JASHS.100.5.447

Tochihuitl-Martiñón, A., Chávez-Franco, S. H., Saucedo-Veloz, C., Suarez-Espinosa, J., & Guerra-Ramírez, D. (2018). Extractos de *Persea Americana* Mill. que retrasan maduración en frutos de aguacate. *Revista Mexicana de Ciencias Agrícolas*, *9*(8), 1639-1650. http://dx.doi.org/10.29312/remexca.v9i8.1720

Xanthakis, E., Havet, M., Chevallier, S., Abadie, J., & Le-Bail, A. (2013). Effect of static electric field on ice crystal size reduction during freezing of pork meat. *Innovative Food Science & Emerging Technologies*, *20*, 115-120. http://dx.doi.org/10.1016/j.ifset.2013.06.011

Yamamoto, N., Tamura, S., Matsushita, J., & Ishimura, K. (2005). Fracture properties and microstructure of chicken breasts frozen by electromagnetic freezing. *Journal of Home Economics of Japan*, *56*(3), 141-151.

Funding: None.

Received: June 08, 2021; Accepted: July 29, 2022

Associate Editor: Cristina Luisa M. Silva.