OPTIMIZING WALNUT SHELL MECHANICAL PROPERTIES FOR EFFICIENT SHELL-CRACKING USING HEAT TREATMENTS: A COMPARATIVE STUDY OF RADIO FREQUENCY AND HOT AIR HEATING METHODS

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通过热处理优化核桃壳力学性能以实现高效脱壳：射频和热风加热的对比研究

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ABSTRACT

The mechanical properties of walnuts play an influential role in the process of walnut shell-cracking. To determine the optimal mechanical properties of walnuts, the effect of moisture content (MC) on the mechanical properties of walnuts was investigated. The results showed that Rupture force (F), Rupture displacement (D), and Rupture energy (E) of walnuts decreased proportionally with a reduction in the MC. To select an optimal pre-treatment for enhancing the mechanical properties of walnuts prior to shell-cracking, the effects of radio frequency (RF) and hot air (HA) heating treatment to change the mechanical properties of the walnuts were examined. The results indicated that the heating treatments of walnuts could lead to a brittle and easily breakable shell, with the F decreasing from 231.99±34.31 N to 174.73±24.89 N, the D decreasing from 1.68±0.18 mm to 1.36±0.13 mm, and the E decreasing from 207.31±44.29 mJ to 119.47±25.99 mJ. The mechanical properties of walnut shells are optimized to the best condition with the application of either a 2-minute RF treatment, a 3-minute RF treatment, or an 8-minute HA treatment. Notably, RF heating is significantly more time-efficient compared to the HA treatment. Quality evaluation indicated that there were no significant ($p > 0.05$) changes in color values, hardness, and brittleness between the heat-treated walnut kernels and the untreated walnut kernels. Overall, the results obtained from this study demonstrate that RF heating treatment is an effective method for optimizing the mechanical properties of walnuts prior to shell-cracking, and the results may provide guidance for the design and improvement of walnuts shell-cracking processes.

摘要

核桃的力学性能是影响核桃破壳效果的重要因素。为了获取最优的力学性能，研究了含水率对核桃力学性能的影响。结果表明，核桃的破壳力、破壳位移和破壳能均随着含水率的降低而降低。为了确定核桃破壳之前最佳的预处理方法，研究了射频(RF)加热处理和热风(HA)加热处理对核桃力学性能的影响。结果表明，加热处理使核桃壳变脆易碎，F 从 231.99±34.31N 降至 174.73±24.89N，D 从 1.68 ±0.18mm 降至 1.36±0.13mm，E 从 207.31±44.29mJ 降至 119.47 ±25.99mJ；其中，在 RF 2min、RF 3min、HA 8min 三种加热处理方法下，核桃的力学性能达到最优；并且与 HA 加热处理相比，RF 加热处理大大缩短了加热时间。品质分析结果表明，加热处理后的核桃和未处理的核桃仁的颜色值、硬度和脆性没有显著变化（p>0.05）。本研究的结果表明，RF 加热处理是优化核桃力学性能的有效方法，此研究结果可为核桃破壳工艺的设计和改进提供指导。

INTRODUCTION

Walnuts (*Juglans regia L.*) are cultivated worldwide, with the global production of in-shell walnuts reaching approximately 3.87 million metric tons in 2022 (*FAOSTAT, 2022*). Walnut kernels, renowned for their significant medicinal value, are rich in a variety of unsaturated fatty acids, which have been shown to effectively reduce serum cholesterol, blood pressure, and the risk of heart disease (*Guasch-Ferré, et al., 2017; Turek & Wszołek, 2021*). The process of walnut shell-cracking is a pivotal step in the primary processing of walnuts, directly influencing the quality of the end product (*Liu et al., 2021*). There is a substantial price disparity among walnut kernels, with whole walnuts significantly outpricing their fragmented counterparts. This price gap is primarily attributed to the integrity of the walnut kernels; intact kernels fetch a higher market price due to their superior quality and strong consumer demand. However, the task of cracking walnut shells presents a challenge, as they are predominantly composed of lignin and hemicellulose, which make them hard and resistant to breakage (*Antreich et al., 2019; Shi et al., 2023*). Moreover, the minimal gap between the shells and kernels complicates the separation process, hindering the achievement of a high whole kernel yield (*Zhang et al., 2022; Wang et al., 2023*).

Current studies on walnut shell-cracking methods primarily include multi-point extrusion (*Zhang et al., 2022*), impact (*Cao et al., 2017*), combined force (*Wang et al., 2024*), and flexible-belt shearing extrusion (*Liu et al., 2016*), among others. It is also possible to adjust parameters such as speed, angle and spacing to optimize the adaptability of the machine to different types and sizes of walnuts (*Liu, et al., 2021*). However, the current technology for obtaining whole walnut kernels is not satisfactory and people continue to rely on manual labor to extract whole walnut kernels. Manual walnut shell-cracking methods are fraught with issues, including low processing efficiency, high costs, and concerns over food hygiene. Therefore, there is an urgent need for the development of equipment and methods that can achieve a high whole kernel yield.

Moisture content (MC) is a critical parameter in nut production, with studies demonstrating its significant impact on the rupture force, rupture energy, specific deformation, and elastic modulus of nut shells (*Altuntas & Erkol, 2011; Maghsoudi et al., 2012*). In conventional engineering, heat treatment is a convenient, economical, and swift method to modify MC. Common heat treatment methods for agricultural products include hot air (HA) heating (*Chen et al., 2020*), radio frequency (RF) heating (*Mao et al., 2021*), microwave heating (*Wang et al., 2022*), and other thermal processes.

RF energy, a non-ionizing form of electromagnetic waves ranging from 3 kHz to 300 GHz, generates heat through the frictional interaction of polarized molecules and charged ions within a product in response to RF fields (*Ling et al., 2023*). As an emerging technology based on electromagnetic waves, RF heating possesses advantages such as high heating rates, volumetric heating, selective heating, and energy efficiency (*Kou et al., 2019; Zuo et al., 2022*). For tree nuts, such as hazelnuts and walnuts, RF heating has been applied for various purposes, including pasteurization (*Zhang Ma, & Wang, 2021*), disinfestation (*Wang et al., 2007*), and drying (*Wang, Tang, & Zhao, 2021*). Concurrently, heat treatment can alter the mechanical properties of materials (*Gao, Li, & Chen, 2023; Hao, et al., 2021; Wang, et al., 2020*). Therefore, the effect of RF heating on the mechanical properties of walnuts warrants investigation and comparison with conventional HA heating.

Therefore, the objectives of this study were to (1) compare the effects of different MC on the mechanical properties of walnuts, (2) compare the changing in mechanical properties of walnuts under different heating treatments, and (3) evaluate walnut kernel quality under different heating treatments.

MATERIALS AND METHODS

Pre-Experiments Investigating the Impact of MC on Walnut Mechanical Properties

Walnut samples were procured from the Xinjiang Production and Construction Corps, with the cultivar selected being Wen 185. To mitigate moisture loss and damage to the walnuts, the green walnuts underwent drying and compression tests following the removal of the green husk and washing. The initial MC of the walnut shells was 31.30 ± 2.14% following the AOAC Official Method 925.40 (AOAC, 2002). A drying treatment was processed for the walnuts to obtain samples at different MC, then followed by compression tests to study the effect of MC on mechanical properties of walnuts.

For each HA drying experiment, the preset temperature was set at 60°C to ensure kernel quality (*Man, et al., 2024*). Based on the experiments conducted on the relationship between MC and HA drying time, walnuts with HA drying times of 0, 4, and 10 hours were selected for compression experiments. After each HA drying session of the walnuts was completed, they were cooled to room temperature and compression tests were carried out immediately, with each test group repeated five times. The walnuts were dried to approximately 8% MC, placed in ziplock bags, and stored in a dry room for use in the subsequent part of the study.

Compression test and mechanical parameters

An electronic universal testing machine (DDL10, Changchun, China) was used for the compression test with an effective force range of 0~10 KN and a loading speed range of 0.01~1000 mm/min (Fig 1). The compression system mainly consists of a computer, a compression structure, and sensors. Upon commencement of the actual compression process, the deformation of the specimen induces varying forces. The sensors are capable of detecting these force and displacement changes, subsequently conveying this data to the computer for analysis.

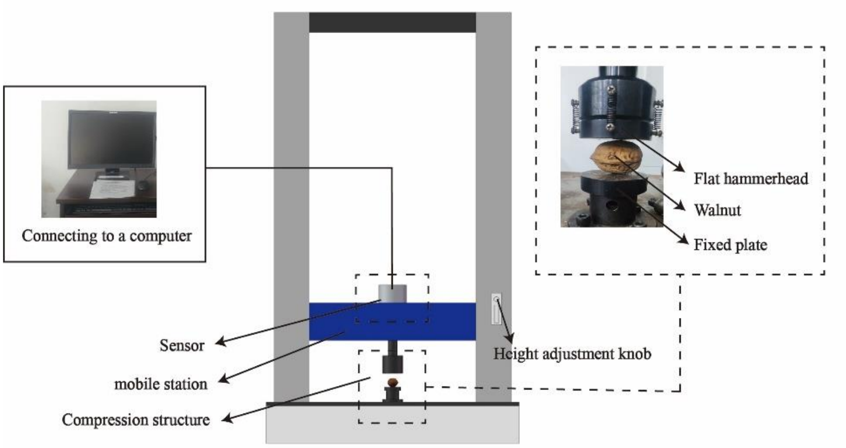

Fig. 1 – Schematic diagram of Mechanical Compression System

As depicted in Fig. 1, the compression experiment was conducted along the thickness direction of the walnuts. A flat hammer head was chosen for the compression, and the compression speed was set at 10 mm/min. Fig. 2 shows a typical force-displacement curve for compressed walnuts. It is evident from Fig. 2 that the compressive deformation process of the walnuts can be bifurcated into two distinct stages: an initial elastic deformation stage, prior to rupture, followed by a crack expansion stage post-rupture. The mechanical properties of walnut kernels are predominantly characterized by three parameters: rupture force (F), rupture displacement (D), and rupture energy (E). F (N) and D (mm) represent the force and displacement at the point of fracture, respectively, obtained from the data points exported from the electronic universal testing machine. The E (mJ) was determined from the chart by measuring the area under the force-deformation curves (Koyuncu, Ekinci, & Savran, 2004). By numerically integrating the force and displacement data points in the 0-D compression range derived from the electronic universal testing machine using the compound trapezoidal formula, the value of E can be derived as follows (*Sauer, 2011*):

$$E = \int_0^D f(x)\,dx \approx \frac{h}{2}\left(y_0 + y_m + 2\sum_{i=1}^{m-1} y_i\right) \tag{1}$$

where:

D (mm) is the transverse coordinate of the rupture point, the value of m is the number of data points minus 1 in the 0-D interval for each set of compression tests, $h = D/m$, y_i (N) are the values of the longitudinal coordinates of each data point.

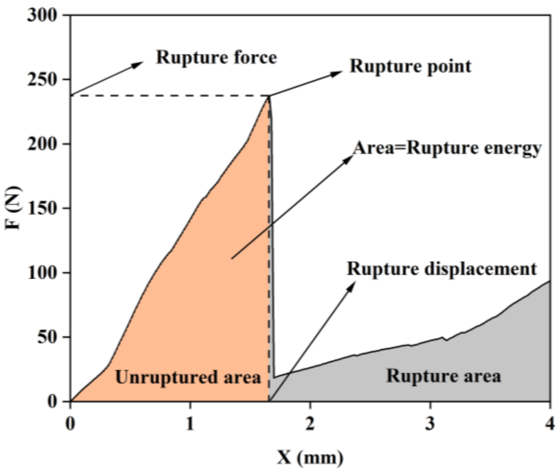

Fig. 2 – The classic force-displacement diagram of a walnut, showing the definitions of Rupture force (N), Rupture displacement (mm), and Rupture energy (mJ)

RF heating treatment

A 6 kW, 27.12 MHz free-running oscillator RF system (SO6B, Strayfield International, Wokingham, UK) associated with a HA system supplied by a 6 kW electric heater (Fig. 3) was used to heat walnuts (*Wang et al., 2010*).

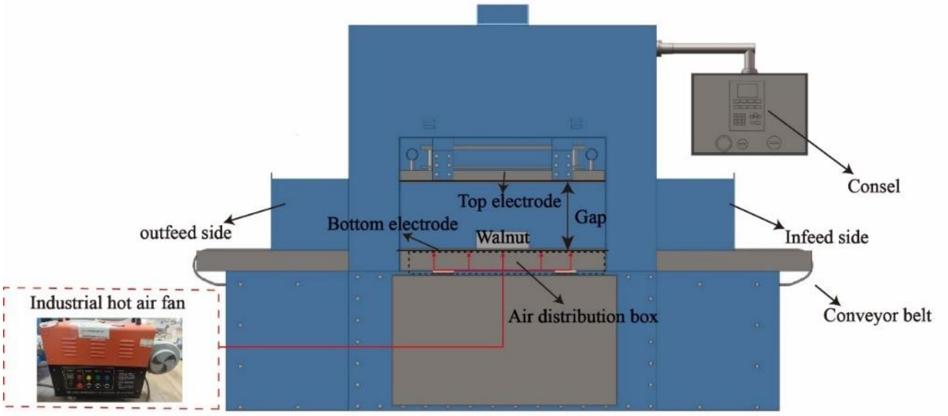

Fig. 3 – Schematic diagram of RF system

Approximately 750 g of the walnut samples were placed in a plastic container (300 mm × 250 mm × 80 mm) made of PP (Fig. 4a), which had a perforated bottom wall to allow HA to pass through the sample from the bottom, effectively expelling water vapor during the process. Before each heat treatment, the walnuts underwent a brief surface wetting procedure to clean and maintain them in the same initial conditions. According to the method proposed by *Jiao et al. (2012),* the electrode gap of 100 mm was selected for improve the evaporation of the water on the walnut surface. To obtain the optimum heating effect, the RF treatment time was carried out for 1, 2, and 3 min, respectively. To evaluate the effect of RF heating on the mechanical properties of walnuts, 15 walnuts were used in the compression test and labelled to occupy one quarter of the plastic container (Fig. 4b).

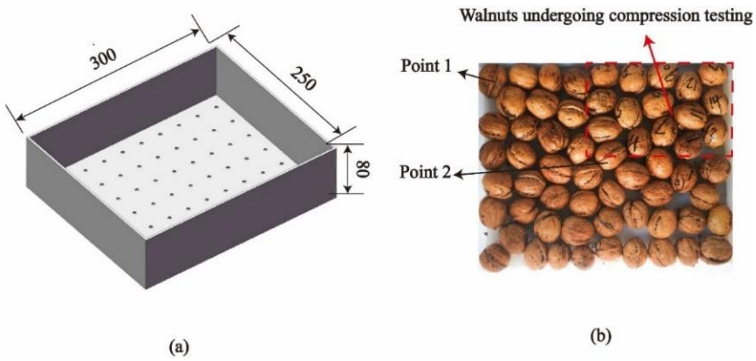

Fig. 4 – Arrangement of heat-treated walnut and fiber optic insertion point (a), shape and size of box (b) (mm)

Two methods were used to record the temperature during the heating process. Two probes of a six-channel fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) were inserted into two walnuts in the center of the vessel through pre-drilled holes in the walnut shells (Fig. 4b). The samples were photographed with an infrared thermographic camera (A300, FLIR System, NH, U.S.) to obtain the temperature distribution on the walnuts surface. After the walnuts had completed the RF heating, the samples were quickly removed from the RF chamber. The heated 15 labelled walnuts were then quickly transferred to an electronic universal testing machine for compression testing (approximately 15 minutes).

HA heating treatment

To evaluate the effect of HA heating on the mechanical properties of walnuts and compare it with RF heating treatment, an electrically heated blast heater (DGG-AGG-9030A, Shanghai, China) was used to heat the walnuts (Fig. 5). The temperature of 60°C was selected in the HA heating test same as the HARF heating (*Zhang et al., 2016*). The walnuts were placed in plastic containers and the containers were placed in an electric radiation drying oven (Fig 5a).

The temperatures of the kernel and shell of walnuts were measured separately using a six-channel fiber-optic temperature sensor system and an infrared camera. Based on the thermal characteristics of HA heating, 8 minutes (the average temperature of walnut shells was not significantly different from that of RF heating for 2 minutes) was selected as the experimental temperature for comparison with the optimal treatment of RF heating. Similar to the RF heating treatment, 15 walnuts used for the compression experiment were placed in a quarter of the plastic container (Fig. 4b). When the HA heating of the walnuts was completed, the walnuts were quickly transferred to the electronic universal testing machine to complete the compression test (approximately 15 min).

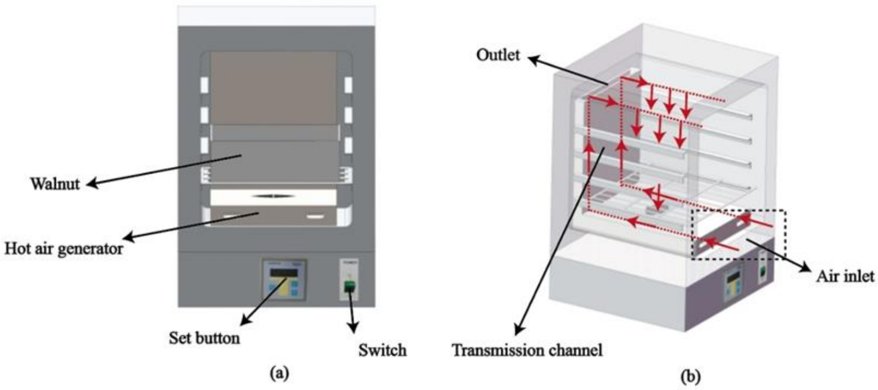

Fig. 5 – Schematic diagram of HA heating system

Evaluation of walnut kernels quality

The color of walnut kernel samples was measured with a computer vision system (CVS) reported before (*Tang et al., 2008*). Photographs of the samples taken by the camera were utilized to capture the values of L*, a*, and b* of samples as follows (*Hou, Ling, & Wang, 2015; Kong et al., 2007*):

$$L^*=\frac{L}{2.5} \tag{2}$$

$$a^*=\frac{240}{250}a-120 \tag{3}$$

$$b^*=\frac{240}{250}b-120 \tag{4}$$

where:

*L** denote the brightness values of walnut kernels, *a** stand for the red-green values of walnut kernels, and *b** indicate the blue-yellow values of walnut kernels. The color values of walnut kernels from untreated, RF 1min, RF 2min, RF 3min, and HA 8min walnuts were measured using the aforementioned method on five separate occasions.

Hardness and brittleness of walnut kernels were determined using a texture analyzer (TA.XTC-18, Baosheng Industrial Development Co., Ltd., Shanghai, China) fitted with a TA/2 cylindrical probe (*Jiao et al., 2022*). A quarter of the walnut kernels were placed on a flat surface, a compression test was applied using a cylinder probe, and a test speed of 1.0 mm/s. Texture properties were measured and calculated by the given software.

RESULTS AND DISCUSSION

Effect of water content

The changes in MC of walnut shells after HA drying are shown in Fig 6. The MC of walnut shells decreased as the drying time increased, with the drying rate gradually decreasing, which was in accordance with the typical drying curves of food and agricultural materials (*Chen et al., 2020*). Walnuts were selected for compression tests with the MC of 31.30 ± 2.14%, 14.27 ± 1.99%, and 6.49 ± 0.46%, corresponding to the drying time of 0, 4, and 10 hours, respectively. The results showed that the values of F, E, and D decreased significantly as the MC decreased (Fig. 7). This observation indicates that when the MC is high, the shell has a greater resistance to cracking. The lower MC tends to result in walnut shells with reduced mechanical properties, making them more susceptible to breakage. However, there was no significant changes between the D and E values when the MC was below 14.27 ± 1.99%. It can be concluded that the mechanical properties of walnuts do not change significantly at a certain level of MC and that further reduction of the MC of walnuts will only increase the cost.

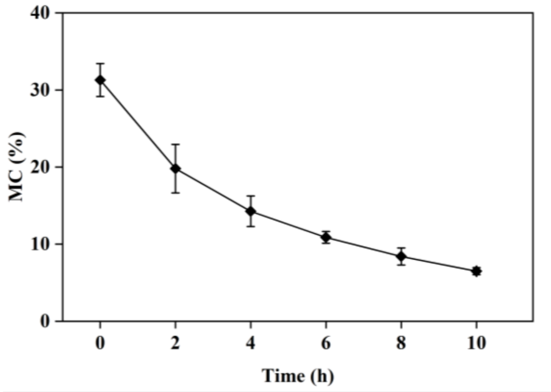

Fig. 6 –Drying curve of the sample (mean ± SD of two replicates)

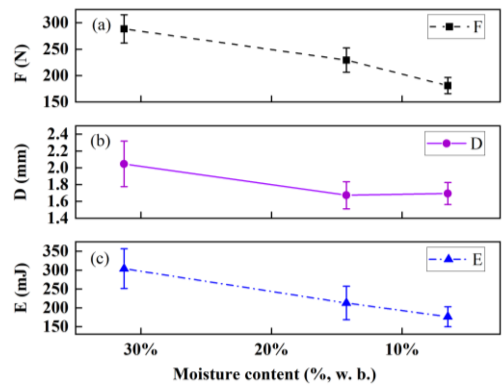

Fig. 7 –Samples rupture force-MC (a), rupture displacement-MC (b) and rupture energy-MC (c) (mean ± SD of five replicates)

Evaluation of RF heating treatment

Fig. 8 illustrates the heating profiles of walnuts at both the edge and center positions. The heating rate of the walnut at the edge is higher than at the center due to the edge effect of RF heating, which is consistent with the findings of other researchers (*Dong et al., 2023; Hou, Zhang, & Wang, 2021*). After three minutes of heating, the highest temperature inside the walnut only reached 57.95°C ± 2.33°C, which helps to preserve the quality of the walnut kernels. From Fig. 9, it is evident that the F value significantly declined, whereas the alterations in D and E are less discernible, when the heating time is 1 min. This observation can be explained by the minimal water evaporation (approximately 46.77%) and the low surface temperature (approximately 44.06°C) of the walnut shells during the heating process. Consequently, the mechanical properties of the walnut shell remain largely unaltered. As shown in Fig. 9 (b) and Fig. 9 (c), the D value of walnuts were 1.66±0.16 mm, 1.36±0.13 mm and 1.39±0.14 mm, and the E value of walnuts were 152.51±40.81 mJ, 119.47±25.99 mJ and 120.45±29.28 mJ, subjected to the heating time of 1, 2, and 3 min, respectively. The mechanical properties of walnuts show no significant changes after more than 2 minutes of RF treatment. This may be due to the fact that the water on the surface of the walnuts was almost evaporated after 2 minutes (approximately 82.25%, no significant from the time of 3 min), and longer heating time did not significantly affect the mechanical properties of the walnuts. As shown in Figure 10, after 1 minute of RF treatment, the walnut surfaces displayed multiple low-temperature zones, indicating residual unevaporated water. As the treatment duration extended to 2 minutes, these low-temperature areas became inconspicuous, suggesting that the water on the walnut surfaces had substantially evaporated. This observation underscores the effectiveness of RF treatment in accelerating the evaporation process, efficiently removing water from the walnut surfaces.

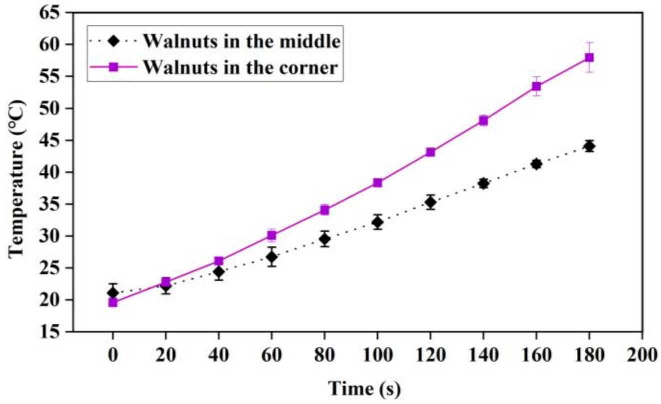

Fig. 8 – Heating curves of the interior of walnuts located in the edges and middle of the box (mean ± SD of two replicates)

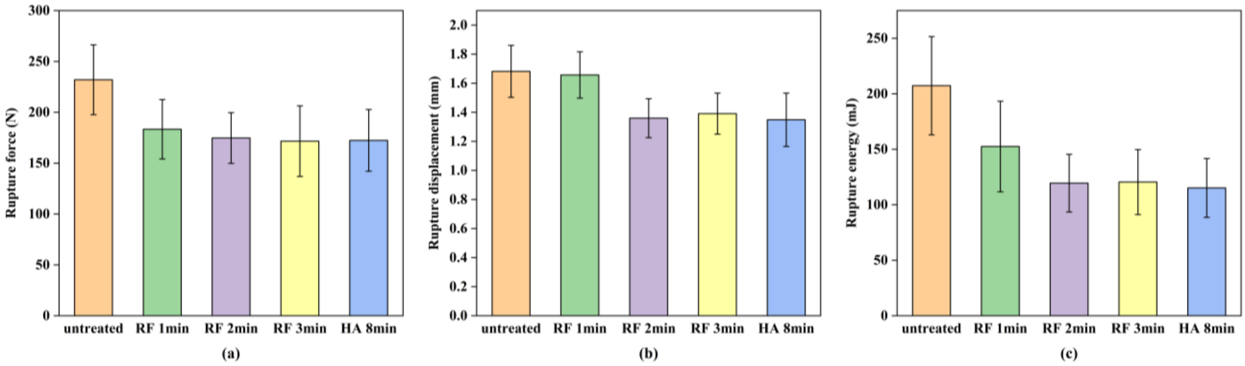

Fig. 9 – Changes in rupture force (a), rupture displacement (b) and rupture energy (c) after heating treatment (mean ± SD of fifteen replicates)

Comprehensive evaluation of HA heating and RF heating

In Fig. 8 and Fig. 11 it is demonstrated that RF heating achieves a higher heating rate compared to HA heating. The HA heating process requires 8 minutes to raise the average temperature of the walnut shell to about 50°C, whereas RF treatment accomplishes this in just 2 minutes. Table 1 shows the effect of different heating times for RF and HA on the mechanical properties of walnuts. According to the different mechanical properties of the walnuts, the walnuts were classified into three grades: A, B and C. Grade A (RF 2min, RF 3min, HA 8min): The mechanical properties of the walnut shells have been optimized to the greatest extent possible, resulting in a brittle and easily breakable shell. Grade B (RF 1min): An initial improvement in the mechanical properties of the walnut shells is observed, indicated by a significant reduction in F; however, there is no significant reduction in D, which is the factor most associated with kernel damage. Grade C (untreated): The walnuts remain untreated, resulting in tough shells that are difficult to break open to extract the kernels. Consequently, utilizing RF heating for 2 min represents the optimal pre-treatment strategy prior to the process of walnut shell-cracking.

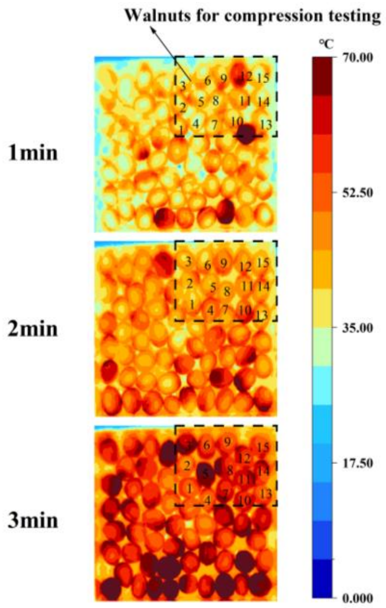

Fig. 10 – Temperature distribution of walnut surface after different RF treatment times

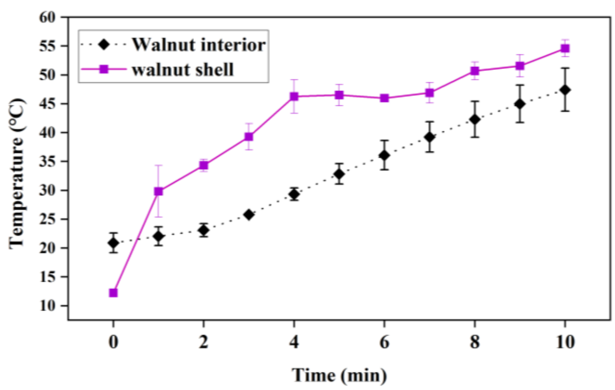

Fig. 11 – Heat-up curves of walnut shell and kernel under 60°C HA heating (mean ± SD of two replicates)

Table 1

Mechanical properties of walnuts under different heating treatments (mean ± SD of fifteen replicates)

Variable	untreated	RF 1 min	RF 2 min	RF 3min	HA 8min
F **(N)**	231.99±34.31^{a}#	183.35±29.18^{b}	174.73±24.89^{b}	171.60±34.72^{b}	172.39±30.28b
D **(mm)**	1.68±0.18^{a}	1.66±0.16^{a}	1.36±0.13^{b}	1.39±0.14^{b}	1.35±0.18^{b}

Mechanical properties of walnuts under different heating treatments (mean ± SD of fifteen replicates)

Variable	untreated	RF 1 min	RF 2 min	RF 3min	HA 8min
E (mJ)	207.31±44.29^{a}	152.51±40.81^{a}	119.47±25.99^{b}	120.45±29.28^{b}	115.14±26.52^{b}
Grade	C	B	A	A	A

(#Different lower-case letters within a row indicate that means are significantly different at P < 0.05 among different treatments.)

Quality evaluation

The quality of walnut kernels was analyzed. As demonstrated in Table 2, there was no significant effect on the hardness, brittleness, and color values of the walnuts (p > 0.05), when RF treatment was applied for 1, 2, and 3 minutes, or HA treatment for 8 minutes. This is because the heating time is short (less than 8 min) and the heating temperature is low (not exceed 60°C). RF heat treatment, which changes the mechanical properties of the shell, does not affect the quality of the kernel while changing the mechanical properties of the shell. This process is suitable for industrial applications.

Table 2

System irrigation test Quality parameters of walnut kernel samples treated by under different heating treatments (mean ± SD of five replicates)

variable	untreated	RF 1 min	RF 2 min	RF 3min	HA 8min
Hardness (gf)	1043.71±256.22^{a} #	1001.54±179.73^{a}	1099.31±79.35^{a}	1204.64±251.07^{a}	1058.73±218.28^{a}
Frangibility (gf)	761.53±124.92^{a}	757.58±170.46^{a}	816.97±154.45^{a}	664.31±88.10^{a}	790.28±172.24^{a}
*L**	45.39±3.16^{a}	46.37±2.43^{a}	48.89±3.76^{a}	47.87±1.03^{a}	48.33±2.77^{a}
*a**	5.91±1.00^{a}	6.31±0.90^{a}	5.44±0.97^{a}	5.51±0.27^{a}	5.87±0.67^{a}
*b**	26.47±1.24^{a}	25.94±0.78^{a}	25.55±1.19^{a}	25.22±1.58^{a}	26.91±0.83^{a}

(#Different lower-case letters within a row indicate that means are significantly different at $P < 0.05$ among different treatments.)

CONCLUSIONS

The objective of this paper was to propose a method for optimizing the mechanical properties of walnut shells by a heating treatment. The results of the heating treatment experiments demonstrated that 2-minute RF, 3-minute RF, and 8-minute HA heating treatments were effective in reducing the F, D, and E values of walnuts. Among them, under 2-minute RF treatment, F decreased from 231.99±34.31 N to 174.73±24.89 N, D decreased from 1.68±0.18 mm to 1.36±0.13 mm, and E decreased from 207.31±44.29 mJ to 119.47±25.99 mJ, which will help to crack the walnut shells. Moreover, 2-minute RF can significantly reduce time costs compared to other methods, making it the optimal treatment process for walnut shell-cracking. The results of the quality analysis demonstrated that the 2-minute RF process had no significant (p > 0.05) effects on the hardness, brittleness and color values of walnut kernels, making it suitable for industrial application. Future research may be conducted to investigate the impact of RF heating on the performance of walnut shell-cracking machinery.

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