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Modifications on the Processing Parameters of Traditional Pineapple Slices by Stabilized Sound Pressure of Multiple Frequency Ultrasonic-Assisted Osmotic Dehydration

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Abstract: This study investigated the practical feasibility of synergistically and optimally applying ultrasound-assisted osmotic dehydration (UAOD) practices for the pineapple slice picking process (in sugar osmotic solution), with potential implications for improving current practices. This study was carried out to evaluate the effects of different treatment conditions of single (40 and 80 kHz)/multiple (40/80 kHz) frequencies, output powers (300, 450, and 600 W), and treatment time (5–40 min) at 30, 45, and 60 °Brix applied, respectively, on the pineapple slices picking process. The sound pressure of the UA was also measured to confirm that it provided the corresponding effect stably under different conditions. The ideal UAOD operating condition for pineapple slices is a 45 °Brix sugar osmotic solution, with frequency multiplexing at 40/80 kHz and an output power of 450 W for 25 min, which yields the optimal solids gain (SG) rate of 7.58%. The above results of this study indicated that UAOD could improve the accelerated quality transfer of pineapple slices and enhance the final product quality, thereby increasing the efficiency of the dehydration process and saving processing costs and time.

Keywords: energy saving; solids gain; sound pressure; time saving

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1. Introduction

Including fruit in one's daily diet is vital for maintaining a healthy lifestyle [1,2]. Fruits are highly regarded as an abundant source of vital nutrients, including vitamins, fiber, polyphenols, and enzymes [2,3]. These nutrients can potentially mitigate the risk of metabolic diseases, notably cardiovascular disease and cancer [1,2]. This practice is of paramount importance to individuals who value their overall well-being. However, several processing and preservation methods have been developed to extend the shelf-life of fruits. These methods, such as canning, UAOD, drying, freeze drying, delayed pre-cooling, post-ripening, pulsed electric field (PEF), coatings, and activated packaging, have been implemented to ensure that food maintains its high nutritional quality and safety standards [3–7].

Osmotic dehydration (OD) is a process that utilizes osmotic pressure to transfer water and soluble substances from the cells of fruits and vegetables into the intercellular space, thereby equalizing the osmotic pressure on both sides of the cell membrane [5,8,9]. However, the efficacy of treatment without assisted processes is significantly influenced by the quality transfer efficiency, which is determined by the duration of the treatment process and its effect on water loss and solids gain (SG) efficiency [5,10,11]. It is noteworthy that on certain occasions, the external layer of a product may undergo a more rapid desiccation process than the inner layer [9]. This can form a rigid, impenetrable surface layer that retains excessive moisture within the product [9]. These phenomena precipitate uneven drying of product quality and shelf-life (the proliferation of microorganisms, such as yeast, mold, and bacteria) [2,9,12]. Moreover, the UA (non-thermal) process also causes the inactivation of endogenous enzymes (pectinases, starch enzymes, γ-glutamyl transpeptidase, polyphenol oxidases (PPO), peroxidases, alkaline phosphatase, lactoperoxidase, etc.) in foods [11,13,14]. This approach holds great significance in enhancing the storage stability of processed food products (to maintain a certain level of flavor, texture, freshness, and nutrient quality) [13]. Considering these factors to optimize OD treatment efficiency and achieve desired outcomes is crucial. However, several techniques (UA, pulse vacuum, high pressure, centrifugal force, gamma irradiation, and microwave) have been studied to optimize mass transfer and sustain product quality [11,15]. UA technology utilizes both low energy (high frequency, over 100 kHz, and low power) and high energy (low frequency, 20–100 kHz, and high power) to create high-pressure zones (100 MPa) and micro-cavitation bubbles in a solution [9,16,17]. When the bubbles reach their resonance radius, they collapse, generating extremely high temperatures of up to 5500 °C, known as the cavitation effect [17]. Apart from compromising the structural integrity of the food cell membrane, which can be compromised, effects of this kind can also enhance the mass transfer of water and solutes across the food cell membrane, thus accelerating the dehydration process [8,11]. Moreover, applying mechanical stress, commonly known as the sponge effect, can be an effective means of modifying the structure of food, contingent upon the physical properties of the material in question [18,19]. Fresh foods with thin, soft, and porous tissue structures are more apt to respond positively to this treatment than denser and thicker bioproducts [2]. However, appropriate pre-processing methods (peeled, sliced, etc.) may still yield improvements for thicker, more viscous materials. Combining multiple frequencies (or multifrequency) of ultrasound offers several advantages and better performance. These include enhanced power, improved resonance, increased number and distribution of homogeneous cavitation bubbles, enhanced implosion strength, promoted water loss and SG of the product, inhibited endogenous enzymes, and retained bioactive substances [5,16,20–22]. Moreover, the UA technology, either as a pre-treatment or as part of a combination process, demonstrated significant potential to enhance sustainable food processing efficiency and reduce energy consumption [16,23–25]. The technology has exhibited potential as a sustainable solution (related to the ten goals of the United Nations Sustainable Development Goals (SDGs)) for food processing in the industry, while compared to other equipment, and the cost-effectiveness lends further appeal to its implementation [19,26].

Therefore, this study aimed to determine the feasibility of incorporating UA technology and OD used in synergy into pineapple processing practices while expecting to facilitate improving economic efficiency and product quality. This study investigated the impact of different UAOD processing conditions on the pineapple process; the conditions comprised single (40 and 80 kHz)/multiple (40/80 kHz) frequencies, output powers (300, 450, and 600 W), and processing time (5–40 min), while the sugar osmotic solutions used were at 30, 45, and 60 °Brix. In addition, this study also intended to identify the sound pressure values and explore the effects of solid gain (SG) and browning enzymes' (PPO and peroxidase) residual activities on the UAOD optimal operating conditions for the pineapple process.

2. Materials and Methods

2.1. Materials

Pineapples (Cayenne × Rough, called *Ananas comosus* gold diamond or Tainung No. 17; origin: Gaoshu Township, Pingtung; the three batches used in this study were during the harvest season from June to August 2023) with an average fruit weight of 1.4 kg were purchased from the local market (Taipei, Taiwan). Cane sugar (premium) was purchased from Taiwan Sugar Co. (Tainan, Taiwan). Unless explicitly stated otherwise, all chemicals utilized in this study were procured from Sigma-Aldrich® (Merck KGaA, Darmstadt, Germany).

2.2. Pre-Treatment of Pineapple and Osmotic Solution

The pretreatment of pineapples and the preparation of osmotic solutions were based on the method described by Amami et al. [8] with slight modifications. The fruits were washed with deionized water, peeled, and de-crowned with a stainless-steel knife, and the pulp was sliced into pieces (the average diameter and thickness were 7 ± 1 cm and 0.9 ± 0.1 cm, respectively). Next, the sugar osmotic solutions were formulated at 30, 45, and 60 °Brix (*w*/*w*). Subsequently, UAOD was performed for pineapple processing.

2.3. Determination of Viscosity

All the sugar osmotic solutions in this study were measured by a rheometer (DVNext, AMETEK Brookfield. Inc., Middleborough, MA, USA) and performed in accordance with standard procedures provided by the manufacturer. Briefly, the sample's viscosity was measured using a UL Adaptor accessory with a sample size of about 16 g at a speed of 5 rpm at different temperatures (20 ± 1, 24 ± 1, and 28 ± 1 °C).

2.4. Determination of Sound Pressure

The sound pressure (expressed in mv) of the UA machine (DU302-18L, Ringtech Instruments Co., Ltd., Taichung, Taiwan) was evaluated by measuring the dimensions of the UA's tank (length: 41 cm, width: 30 cm, height: 15 cm) at nine points (3 × 3), including the anterior, middle, and posterior positions. Briefly, the probe of the UA pressure meter (MUE18T, Modern Ultrasonic Engineering Co., Ltd., New Taipei City, Taiwan) was placed 3.5 cm below the solution surface. Then, the sound pressure at different UA frequencies (single frequency 40, 80 kHz, and multiple frequency 40/80 kHz) and output powers (300, 450, and 600 W) was measured. Moreover, the measurements were also carried out at varying concentrations (0, 30, 45, and 60 °Brix) of sugar osmotic solution at different temperatures (20 ± 1, 24 ± 1, and 28 ± 1 °C).

2.5. Determined Rate of Solids Gain (SG)

The indicator SG rate for pineapple was calculated based on the formula described by Fernandes et al. [27], as detailed below:

$$Rate\ of\ solids\ gain\ (SG) = \frac{Wf \times Xsf - Wi \times Xsi}{Wi} \times 100 \tag{1}$$

where

Wi is the initial pineapple weight (g);
Wf is the final pineapple weight (g);
Xsf is the final soluble solids content (%) of pineapple;
Xsi is the initial soluble solids content (%) of pineapple.

2.6. Determination of Sugar Concentration

The sugar concentration (as °Brix) of pineapple was determined following the method described by Wu et al. [28]. First, the UAOD-treated pineapple surface solution was dried with a paper towel. Then, 1 g of the sample was taken, added to 10 mL of deionized water, and homogenized by a blender (Oster BO-00001, Sunbeam Products, Inc., Boca Raton, FL, USA). Next, the sample's sugar content was determined using a hand-held refractometer (MASTER-M, Atago Co., Ltd., Tokyo, Japan) and expressed in °Brix.

2.7. Optimum Operating Conditions for Ultrasonic-Assisted Osmosis Dehydration (UAOD) Pineapple Processing

The operational method for UAOD was performed as described in Corrêa et al. [29] and Xu et al. [20] with minor modifications. The different UAOD treatment conditions mentioned above (Section 2.2) were used to evaluate the effects of each other on the processing of pineapple. In addition, the control group was not subject to any treatment, namely only pickling in sucrose solution (45 or 60 °Brix).

2.7.1. Frequency

Pineapple slices were processed with sugar osmotic solution (45 and 60 °Brix) at different UA treatments (single frequency 40, 80, and multiple frequency 40/80 kHz) for 0.5 h, followed by continued pickling for another 5.5 h.

2.7.2. Output Power

The above process was repeated with the multiple frequency of 40/80 kHz and different output powers (150, 300, 450, and 600 W) to identify the most appropriate output power.

2.7.3. Ultrasonic-Assisted (UA) Processing Time

Pineapple slices were processed with the sugar osmotic solutions (45 and 60 °Brix) and were subjected to pickling treatment for 40 min at 40/80 kHz and 450 W UA. The SG rate was monitored for 5 min during the process.

2.7.4. Sugar Osmotic Solution

The pineapple slices were subjected to different sugar solutions (30, 45, and 60 °Brix) for 30 min treatment, according to the above optimal UA treatment conditions (40/80 kHz and 450 W), and then pickled for another 5.5 h. The rate of SG was examined at intervals of 5, 10, 20, 30, and 60 min, followed by analysis for each hour of pickling.

2.8. Determination of Polyphenol Oxidase (PPO) and Peroxidase Residual Activities

The sample was pre-treated, as described above (Section 2.6). The supernatant was then taken for enzyme residual activity analysis. Briefly, PPO and peroxidase activity measurements were performed as described by Cao et al. [30]. The absorbance values were measured at 420 and 470 nm, while PPO and peroxidase residual activities were calculated according to the following formula, respectively.

$$Residual\ activity\ (\%) = \frac{Processed\ enzyme\ activity}{Unprocessed\ enzyme\ activity} \times 100 \tag{2}$$

2.9. Statistical Analysis

The data presented in this study were expressed as means ± standard deviation (SD), with triple replicates performed for all trials. The statistical analyses used the software for the statistical product and service solution (SPSS 26, International Business Machines Corporation (IBM) Co., Armonk, NY, USA). The analysis of variance (ANOVA) was used to analyze the differences between groups, and Duncan's multiple range test was used to detect the significant differences where $p < 0.05$.

3. Results and Discussion

3.1. Effects of Different Ultrasonic-Assisted Parameters on the Sound Pressure

3.1.1. Frequency

This study showed that the sound pressure values were insignificantly different at all nine points for different concentrations of sugar osmotic solutions permeated with the 300 W output power and different frequencies (Table 1). This indicates that this UA's low-/high-frequency design provides for stabilized sound pressure. In terms of different frequencies, this study operated with the single (40 or 80 kHz) frequency condition, and multiple frequency conditions showed significant differences ($p < 0.05$) within each condition. In particular, the sound pressure value for each condition decreases with the concentrations of sugar osmotic solution, and the value decreases by about 60 to 70% at increasing from sugar concentrations of 0 to 60 °Brix. This can be attributed to the increased viscosity of the sugar osmotic solution as the concentration increased (Table S1), which impeded the UA output energy being blocked in the mediator, thereby decreasing the sound pressure. Based on a report by Moreira et al. [31], there has been a notable elevation in the required stirring parameter to mix glycerol solutions. As per the report, this increase was attributed to the concentrations of both solutes and solvents. It is worth mentioning that the sound pressure value of the multiple frequencies at 60 °Brix was 4.5 higher than that of single frequencies at 40 kHz (2.9) and 80 kHz (3.3). This study indicated that identical UA systems produce varying sound pressures under similar operating conditions in pure water and sugar solutions, providing distinctive effects, which agreed with the results reported by Cárcel et al. [32]. Moreover, this phenomenon may be attributed to the resonance effect and the subsequent reduction of standing wave formation by multiple frequencies, thereby contributing to a more comprehensive range of energy output during high concentrations of sugar osmotic solutions [22]. Therefore, the optimal function of the multiple frequency UA is intricately linked to the underlying mechanisms of energy transfer, which ultimately determines the efficiency and effectiveness of the entire process. Moreover, this is a critical factor in maximizing the energy output of sugar osmotic solution, which enhances the productivity of the operations.

3.1.2. Power

This study revealed insignificant differences in sound pressure values at nine points for different UA output powers (300, 450, and 600 W while the other variables were maintained constant) (Table 2). Afterward, the sound pressure values of osmotic solutions containing 0, 30, 45, and 60 °Brix, treated using the same parameters mentioned above, showed a decreasing trend. There were significant differences between the groups ($p < 0.05$). Specifically, the results were also consistent with the above Section 3.1.1; namely, the sound pressure values decreased with the increase in the concentrations (0 to 60 °Brix) of the sugar osmotic solutions. In addition, as per the report of Corrêa et al. [29], two factors may impede the propagation of UA wave energy from the generating source to the sample. The liquid medium properties may be an obstacle to this propagation. Secondly, the fibrous structure of the pineapple may render the penetration process less effective, necessitating a more intensive UA treatment. It is worth mentioning that the sound pressure values of 300, 450, and 600 W output powers at 45 °Brix in multiplex frequency were decreased by 26.4, 23.0, and 24.0%, respectively, compared to the control group. According to the report from Cárcel et al. [32], the application that employs high-powered UA has the potential to affect the sound waves of the medium, resulting in varied impacts on related products or processes. The results of this study support the previously mentioned findings. Therefore, this also implies that under the conditions (multiplex frequency with 450 W at 45 °Brix), there was less of a decrease in sound pressure for better performance.

Table 1. The changes in sound pressure values at nine positions in the ultrasonic-assisted tank for different frequencies and sugar osmotic solution concentrations at 300 W output power.

Position	**Concentration (°Brix)**											
	0			**30**			**45**			**60**		
	Frequency (kHz)											
	40	**80**	**40/80**	**40**	**80**	**40/80**	**40**	**80**	**40/80**	**40**	**80**	**40/80**
1	7.30 ± 2.02 ^{a}	14.70 ± 0.58 ^{a}	16.30 ± 0.00 ^{a}	6.20 ± 0.29 ^{a}	14.00 ± 0.87 ^{a}	15.20 ± 0.58 ^{a}	4.50 ± 0.00 ^{a}	6.80 ± 0.29 ^{a}	11.50 ± 1.00 ^{a}	2.50 ± 0.50 ^{a}	3.30 ± 0.29 ^{a}	4.50 ± 0.00 ^{a}
2	7.70 ± 2.08 ^{a}	15.00 ± 0.87 ^{a}	16.50 ± 0.29 ^{a}	6.80 ± 0.76 ^{a}	14.20 ± 0.76 ^{a}	15.20 ± 0.58 ^{a}	5.20 ± 0.29 ^{a}	6.80 ± 0.29 ^{a}	12.00 ± 0.87 ^{a}	3.20 ± 0.58 ^{a}	2.80 ± 0.29 ^{a}	4.30 ± 0.29 ^{a}
3	7.30 ± 2.02 ^{a}	14.80 ± 0.76 ^{a}	16.00 ± 0.76 ^{a}	6.00 ± 0.50 ^{a}	14.20 ± 0.76 ^{a}	15.00 ± 0.50 ^{a}	4.80 ± 0.29 ^{a}	7.00 ± 0.50 ^{a}	11.70 ± 1.61 ^{a}	2.80 ± 0.58 ^{a}	3.50 ± 0.00 ^{a}	4.30 ± 0.29 ^{a}
4	7.50 ± 1.80 ^{a}	14.80 ± 0.76 ^{a}	16.50 ± 0.29 ^{a}	6.30 ± 0.76 ^{a}	14.00 ± 0.87 ^{a}	15.00 ± 0.50 ^{a}	4.50 ± 0.00 ^{a}	6.50 ± 0.00 ^{a}	11.80 ± 1.53 ^{a}	2.70 ± 0.29 ^{a}	3.20 ± 0.58 ^{a}	4.50 ± 0.00 ^{a}
5	8.00 ± 1.50 ^{a}	15.00 ± 0.87 ^{a}	16.30 ± 0.29 ^{a}	7.00 ± 1.00 ^{a}	14.30 ± 1.04 ^{a}	15.00 ± 0.50 ^{a}	5.30 ± 0.29 ^{a}	6.80 ± 0.29 ^{a}	12.20 ± 1.15 ^{a}	3.20 ± 0.58 ^{a}	3.30 ± 0.58 ^{a}	4.50 ± 0.00 ^{a}
6	7.70 ± 1.61 ^{a}	15.00 ± 1.00 ^{a}	16.50 ± 0.29 ^{a}	6.30 ± 0.29 ^{a}	14.00 ± 0.87 ^{a}	15.00 ± 0.50 ^{a}	5.30 ± 0.29 ^{a}	6.70 ± 0.29 ^{a}	11.80 ± 1.53 ^{a}	3.20 ± 0.58 ^{a}	3.20 ± 0.58 ^{a}	4.50 ± 0.00 ^{a}
7	7.70 ± 1.61 ^{a}	15.30 ± 1.26 ^{a}	16.30 ± 0.29 ^{a}	6.50 ± 0.50 ^{a}	14.30 ± 0.76 ^{a}	15.20 ± 0.58 ^{a}	4.80 ± 0.58 ^{a}	6.80 ± 0.29 ^{a}	12.20 ± 2.08 ^{a}	2.70 ± 0.29 ^{a}	3.50 ± 0.50 ^{a}	4.50 ± 0.00 ^{a}
8	7.70 ± 1.61 ^{a}	15.30 ± 1.26 ^{a}	16.20 ± 0.29 ^{a}	6.50 ± 0.50 ^{a}	14.00 ± 0.87 ^{a}	15.20 ± 0.58 ^{a}	5.30 ± 0.29 ^{a}	6.50 ± 0.50 ^{a}	12.20 ± 1.61 ^{a}	3.20 ± 0.58 ^{a}	3.20 ± 0.76 ^{a}	4.50 ± 0.00 ^{a}
9	7.70 ± 1.61 ^{a}	15.20 ± 1.04 ^{a}	16.00 ± 0.29 ^{a}	6.50 ± 0.50 ^{a}	14.20 ± 0.76 ^{a}	15.20 ± 0.58 ^{a}	4.50 ± 0.50 ^{a}	7.00 ± 0.29 ^{a}	11.50 ± 2.08 ^{a}	2.00 ± 0.50 ^{a}	3.50 ± 0.50 ^{a}	4.50 ± 0.00 ^{a}
Average (mv)	7.60 ± 0.22 ^{d}	15.0 ± 0.22 ^{d}	16.3 ± 0.16 ^{d}	6.50 ± 0.30 ^{c}	14.1 ± 0.13 ^{c}	15.1 ± 0.11 ^{c}	5.00 ± 0.33 ^{b}	6.70 ± 0.16 ^{b}	12.0 ± 0.27 ^{b}	2.90 ± 0.31 ^{a}	3.30 ± 0.22 ^{a}	4.50 ± 0.09 ^{a}

The different superscript lowercase letters in the same column represent the significant differences ($p < 0.05$).

Table 2. The changes in sound pressure values at nine positions in the ultrasonic-assisted tank for different output powers and sugar osmotic solution levels at multiple frequencies (40/80 kHz).

Position	**Concentration (°Brix)**											
	0			**30**			**45**			**60**		
	Power (W)											
	300	**450**	**600**	**300**	**450**	**600**	**300**	**450**	**600**	**300**	**450**	**600**
1	16.30 ± 0.00 ^{a}	17.50 ± 0.50 ^{a}	20.30 ± 0.58 ^{a}	15.20 ± 0.58 ^{a}	17.00 ± 0.50 ^{a}	19.80 ± 0.58 ^{a}	11.50 ± 1.00 ^{a}	13.30 ± 1.04 ^{a}	14.70 ± 1.44 ^{a}	4.50 ± 0.00 ^{a}	4.70 ± 1.04 ^{a}	6.20 ± 0.76 ^{a}
2	16.50 ± 0.29 ^{a}	17.30 ± 0.29 ^{a}	20.70 ± 0.76 ^{a}	15.20 ± 0.58 ^{a}	17.20 ± 0.76 ^{a}	20.70 ± 1.26 ^{a}	12.00 ± 0.87 ^{a}	13.50 ± 1.32 ^{a}	14.50 ± 1.32 ^{a}	4.30 ± 0.29 ^{a}	5.20 ± 0.58 ^{a}	6.70 ± 0.29 ^{a}
3	16.00 ± 0.76 ^{a}	17.30 ± 0.29 ^{a}	20.70 ± 0.76 ^{a}	15.00 ± 0.50 ^{a}	16.80 ± 0.58 ^{a}	20.30 ± 1.04 ^{a}	11.70 ± 1.61 ^{a}	13.20 ± 1.15 ^{a}	14.80 ± 1.15 ^{a}	4.30 ± 0.29 ^{a}	5.00 ± 0.87 ^{a}	6.30 ± 0.76 ^{a}
4	16.50 ± 0.29 ^{a}	17.30 ± 0.29 ^{a}	21.20 ± 0.58 ^{a}	15.00 ± 0.50 ^{a}	17.20 ± 0.58 ^{a}	20.20 ± 1.04 ^{a}	11.80 ± 1.53 ^{a}	13.20 ± 1.15 ^{a}	14.80 ± 1.53 ^{a}	4.50 ± 0.00 ^{a}	4.80 ± 0.76 ^{a}	6.30 ± 0.76 ^{a}
5	16.30 ± 0.29 ^{a}	17.30 ± 0.29 ^{a}	20.70 ± 0.76 ^{a}	15.00 ± 0.50 ^{a}	17.00 ± 1.00 ^{a}	20.50 ± 1.32 ^{a}	12.20 ± 1.15 ^{a}	13.20 ± 1.15 ^{a}	15.00 ± 1.50 ^{a}	4.50 ± 0.00 ^{a}	5.20 ± 0.58 ^{a}	6.30 ± 0.76 ^{a}
6	16.50 ± 0.29 ^{a}	17.50 ± 0.50 ^{a}	21.00 ± 0.87 ^{a}	15.00 ± 0.50 ^{a}	16.80 ± 0.76 ^{a}	20.20 ± 0.76 ^{a}	11.80 ± 1.53 ^{a}	13.30 ± 1.44 ^{a}	15.00 ± 1.50 ^{a}	4.50 ± 0.00 ^{a}	5.20 ± 0.58 ^{a}	6.30 ± 0.76 ^{a}
7	16.30 ± 0.29 ^{a}	17.50 ± 0.50 ^{a}	21.00 ± 0.87 ^{a}	15.20 ± 0.58 ^{a}	16.70 ± 0.76 ^{a}	20.00 ± 1.00 ^{a}	12.20 ± 2.08 ^{a}	13.20 ± 1.61 ^{a}	14.80 ± 1.53 ^{a}	4.50 ± 0.00 ^{a}	4.80 ± 1.15 ^{a}	6.30 ± 0.76 ^{a}
8	16.20 ± 0.29 ^{a}	17.30 ± 0.76 ^{a}	20.80 ± 0.76 ^{a}	15.20 ± 0.58 ^{a}	17.20 ± 0.76 ^{a}	20.50 ± 1.50 ^{a}	12.20 ± 1.61 ^{a}	13.20 ± 1.15 ^{a}	14.70 ± 1.26 ^{a}	4.50 ± 0.00 ^{a}	4.80 ± 0.76 ^{a}	6.70 ± 0.29 ^{a}
9	16.30 ± 0.29 ^{a}	17.50 ± 0.50 ^{a}	20.70 ± 0.76 ^{a}	15.20 ± 0.58 ^{a}	17.00 ± 0.50 ^{a}	20.20 ± 0.76 ^{a}	12.20 ± 2.08 ^{a}	13.20 ± 1.15 ^{a}	14.80 ± 1.53 ^{a}	4.50 ± 0.00 ^{a}	5.00 ± 0.50 ^{a}	6.30 ± 0.76 ^{a}
Average (mv)	16.30 ± 0.16 ^{d}	17.40 ± 0.11 ^{d}	20.80 ± 0.26 ^{d}	15.10 ± 0.11 ^{c}	17.00 ± 0.19 ^{c}	20.30 ± 0.27 ^{c}	12.00 ± 0.2 ^{b}	13.30 ± 0.1 ^{b}	14.80 ± 0.15 ^{b}	4.50 ± 0.09 ^{a}	5.500 ± 0.20 ^{a}	6.4 ± 0.19 ^{a}

The different superscript lowercase letters in the same column represent the significant differences ($p < 0.05$).

3.1.3. Temperature

This study followed the optimal treatment conditions mentioned in Section 3.1.2. The results obtained at different temperatures (20 ± 1, 24 ± 1, and 28 ± 1 °C) showed that the sound pressure values increased progressively with the increase in temperature (Table 3). There were significant differences ($p < 0.05$) observed between the temperatures. It is possible to account for the observed phenomenon by considering the reduction in the viscosity of sugar osmotic solutions resulting from increased temperatures (Table S1). This reduction, in turn, enhances sound pressure. In particular, an increase in the temperature ranges from 20 ± 1 to 24 ± 1°C resulted in an increased sound pressure of 13.8%, which was better than the increase of 5.1% from 24 ± 1 to 28 ± 1 °C. However, since UA is a non-thermal process [11,13,14], no reference has been provided to the temperature variations during UA in our known studies.

Table 3. The changes in sound pressure values at nine positions in the ultrasonic-assisted tank for different temperatures at multiple frequencies (40/80 kHz), 450 W output power, and 45 °Brix sugar osmotic solution.

Position	**Temperature (°C)**		
	20 ± 1	**24 ± 1**	**28 ± 1**
1	13.80 ± 1.15	15.00 ± 0.87	15.80 ± 1.04
2	14.00 ± 1.32	16.00 ± 0.50	16.70 ± 0.76
3	13.80 ± 1.15	15.80 ± 0.58	16.50 ± 0.50
4	13.80 ± 1.15	15.50 ± 1.00	16.50 ± 0.50
5	13.80 ± 1.15	15.80 ± 0.58	16.70 ± 0.29
6	14.00 ± 1.32	16.00 ± 0.50	16.50 ± 0.50
7	13.80 ± 1.61	15.80 ± 0.58	16.50 ± 0.50
8	13.80 ± 1.15	15.80 ± 0.58	16.70 ± 0.76
9	13.70 ± 1.44	15.70 ± 0.76	16.70 ± 0.76
Average (mv)	13.80 ± 0.10 ^{c}	15.70 ± 0.31 ^{b}	16.50 ± 0.28 ^{a}

The different superscript lowercase letters in the same row represent the significant differences ($p < 0.05$).

3.2. Effects of Different Ultrasonic-Assisted Parameters on the Osmotic Dehydration of Pineapple

3.2.1. Frequency

This study showed that the SG rate increased higher than the control group by UAOD treatment groups for 0.5 h (then pickled for another 5.5 h) at 45 and 60 °Brix sugar solution (Figure 1A), and there were significant differences ($p < 0.05$) between all groups. The effectiveness of UA waves of multiple frequencies can be attributed to their ability to disrupt cellular structures, thereby reducing cellular adhesion and creating spaces and fissures in the cell wall [8]. In addition, UA treatment for 20 to 40 min was a promising technique for decreasing the sugar content (more than 30%) in fruits, primarily depending on the fruit tissue structure and the treatment time [26]. It is worth mentioning that the multiple frequency UA treatment provided a better SG increase rate than the single frequency treatment. This was attributed to the single frequency-treated generated standing waves, which impacted the range of its action less uniformly than that of the multiple frequency ones [33]. However, employing a low-frequency range of 20–50 kHz has been recommended to achieve optimal process and productivity due to such frequencies' enhanced mass transfer and cell permeability [34,35]. Therefore, this study indicated that the UAOD treatment with multiple frequencies (40/80 kHz) contributed to the enhancement of the SG rate performance of the pineapple slices.

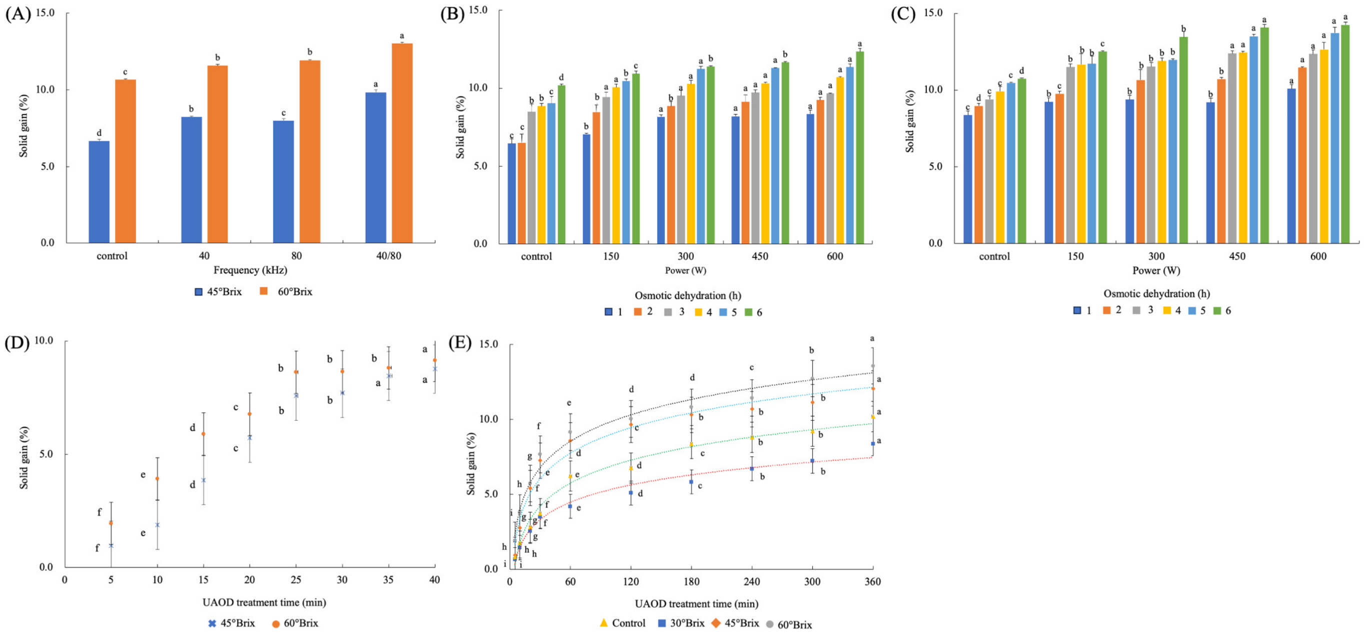

Figure 1. Effects of different ultrasonic-assisted (UA) parameters on the osmotic dehydration (OD) of pineapple solids gain (SG) rate: (**A**) different UA frequencies (single frequency 40 kHz, 80 kHz, and multiple frequency 40/80 kHz) at 45 °Brix and 60 °Brix sugar osmosis solutions; (**B**) different UA output powers (300, 450, and 600 W) at 45 °Brix sugar osmosis solution; (**C**) different UA output powers (300, 450, and 600 W) at 60 °Brix sugar osmosis solution; (**D**) different UA processing times at 45 and 60 °Brix sugar osmosis solution; (**E**) different processing times of multiple frequency 40/80 kHz with output power 450 W at 45 and 60 °Brix sugar osmosis solutions. Different lowercase letters in the figures represent significant differences ($p < 0.05$) (between conditions or groups).

3.2.2. Power

Following the above conditions, the UAOD treatments of pineapple were used at 450 and 600 W for 0.5 h in 45 and 60 °Brix sugar osmotic solutions, followed by pickling for 5.5 h. This study's results indicated that the SG rate of the pickled pineapple increased proportionally with an extended pickling time (Figure 1B,C). There were statistically significant differences ($p < 0.05$) observed between all groups. It is worth mentioning that Li et al. [36] reported an increase in the drying rate with increasing UA intensities, namely with a sharp and rapid decrease in moisture content. This study was not observed due to the utilization of diverse dehydration techniques. Moreover, Amami et al. [8] found that a higher concentration of osmotic solution reduces moisture content and increases the SG rate due to a significant difference in osmotic pressure between the sample and the solution. This phenomenon agreed with the findings of this study. Therefore, the UA treatment facilitates micro-channels forming inside the fruit to eliminate moisture, thus evaporating the moisture inside more readily and improving the quality transfer in the dried fruit [37,38].

3.2.3. Ultrasonic-Assisted Osmosis Dehydration (UAOD) Processing Time

This study administered UAOD treatments to pineapple within 40 min and monitored the SG rate at 5 min intervals. This study indicated that the pineapples' SG rates were saturated with pickled in 45 and 60 °Brix sugar osmosis solutions treated by UAOD for 25 min (Figure 1D). There were significant differences between all conditions ($p < 0.05$). The presence of UA has been found to promote the high osmotic drive of the sugar osmosis solution, which is believed to be the primary explanation for this phenomenon [39]. At the same time, UA will also cause the deformation of internal microscopic channels in the pores of plant tissues, thus promoting water removal by convection and increasing the rate of SG [8,11,19]. The changes observed in pineapple pulp can be attributed to this mechanism.

This study was consistent with the results reported by Li et al. [37] on the SG rate of UAOD treatments that facilitated the osmotic dewatering period of Sanhua plum. Notably, the prolonged duration of UA treatment has been observed to result in a more severe loss of total soluble substances [19]. Therefore, this study was conducted to define the treatment time of the UAOD process of pineapple as 25 min. However, the UAOD period during the multiple frequency pineapple slices contributed to the saving of time spent in the traditional process compared to other products under similar experimental conditions. It is worth noting that the porosity of various fruits and vegetables also influences the efficiency of UA. In particular, dense structures weaken the mechanical effect of UA wave energy [37]. Conversely, Nowacka and Wedzik [40] reported a UA treatment of vacuum-packed carrots for 30 min, while structural changes were observed, and none altered the subsequent drying time required. In addition, the agronomic practices of fruit may be impacted by varying production seasons and climate despite originating from the same source [1,38]. Currently, it has been reported that the UAOD technology has been applied to the dehydration of fruit and vegetable slices such as apples, apricots, potatoes, cranberries, garlic, pumpkins, strawberries, kiwis, papayas, plums, bananas, carrots, persimmons, sour cherries, and tomatoes [11]. This knowledge can enhance the nutritional quality of pineapples by optimizing the processing conditions to retain desirable attributes such as taste, texture, and color. In light of these potential applications, further research is needed to elucidate the precise mechanisms underlying accelerated solute migration in pineapple slices and to identify the optimal conditions for preserving their quality and nutritional value.

3.2.4. Optimum Operating Conditions

In the case of SG, all pickling pre-treatments positively affect the sugar absorption of fruits [38]. This study found that the SG rate of the 30 °Brix sugar osmotic solution was significantly lower than that of the 45 and 60 °Brix groups (Figure 1E) ($p < 0.05$). The possible explanation for the difference can be attributed to the relatively low difference in the solute concentration (osmotic pressure) between 30 °Brix sugar osmotic solution and pineapple slices. In addition, compared to 45 and 60 °Brix, it resulted in a weaker solvent-free mass transfer effect, namely, less sugar osmosis to pineapple slices, resulting in a slower SG rate increase. It is worth mentioning that there were no significant differences in the SG rate increase at 60 °Brix compared to 45 °Brix. This could be explained by the higher concentrations of sugar osmotic solution, which results in higher viscosity. The higher viscosity leads to lower sound pressure values (earlier described results), thus affecting the effectiveness of the UAOD. Despite the high sugar concentration, OD has been suggested to form a robust solid layer on the food's surface, which mitigates mass transfer and reduces the permeability pressure differentials [41]. Namely, the osmotic pressure difference positively correlates with the OD dehydration rate [41]. It was hypothesized that another possible explanation was that the initial OD phase was a rapid diffusion from high to low concentrations, resulting in a rapid increase in the SG rate, whereas the SG rate plateaued over time as the sugar filled the capillaries in the pineapple slices [42]. Subsequently, the accumulation phenomenon observed in pineapple slices leads to increased resistance to outward water transfer into the sugar osmotic solution [42,43]. In addition, the SG rate gradually flattened out following balance at the ultimate concentrations. This result agreed with the results of Feng et al. [44] regarding the garlic slices during the OD process. Other possible interpretations for the increased SG promoted by these physical pre-treatments following OD relate to the damage caused by these treatments to the fruit tissues [45]. Specifically, these include, with no limitation, cell rupture, biochemical reactions following the tissue cell fracture of the fruit, or the disruption of cellular compartments via pectin hydrolysis, leading to cell separation and rupture [45,46]. Therefore, sugar migration into the sample was facilitated by OD migration [46].

Moreover, the diffusion rate between suspended solids and liquids at the boundary of the UA wave field is contingent on both frequency and pressure variables [42]. Therefore, it is crucial to consider both these factors while evaluating the acceleration of diffusion [42]. Upon assessing various factors, such as the ingredients utilized, electric power consumption, and treatment time during practical operation, this study determined that sugar osmosis at 45 °Brix yields a satisfactory SG rate performance, thereby contributing to the efficacy of the UAOD process.

Moreover, this study examined the increase in the SG rate of UAOD treated within 45 °Brix sugar osmotic solution and the control group. Namely, at the same SG rate, calculate the amount of treatment time being shortened by UAOD treatment. The regression curves were used to obtain the equations presented below:

$$Rate\ of\ solids\ gain\ (SG)\ \text{of 45 °Brix sugar osmotic solution group}:\ y = 2.4457 \ln X - 2.2613 \tag{3}$$

$$Rate\ of\ solids\ gain\ (SG)\ \text{of control group}:\ y = 2.213 \ln X - 3.3115 \tag{4}$$

where

y represents the SG rate;

X represents the required UAOD processing time.

The above equations show that the UAOD treatment time decreased by 50–60% for increased SG rates of 4.0–9.0% (Table 4). In particular, the UAOD treatment time was reduced by 51.9%, while the SG rate was increased by 4.0 and 61.7% for an increased 9.0% SG rate. Therefore, this study proved that the treatment of sugar osmotic solution at 45 °Brix for 25 min via multiple frequencies (40/80 kHz) and 450 W output power were the optimal operating conditions for the UAOD process. Corrêa et al. [29] reported that the treatment with UA proved instrumental in the loss of water and SG rate increase while facilitating a marked shortening of 22% (1.6 h) in the subsequent drying time of pineapples. Moreover, it is imperative to consider the product's attributes and the medium employed for its dissemination to evaluate UA's impact accurately [32]. It is paramount to underscore that reducing the processing time may denote a concomitant decrease in energy consumption, a salient point given that drying represents a high-cost, single-unit operation within the food industry, owing to its prodigious time and energy requirements [47–49]. This approach substantially increased the SG rate while offering the most economically viable benefits. Despite UAOD's reduced processing cost, its high sugar content raises health concerns [26,50]. However, complete avoidance may not be feasible, especially for those with limited access to fresh fruits. Therefore, a more moderate approach is recommended, which entails consuming UAOD's products in moderation to balance the nutritional value with potential health risks. Hence, individuals can enjoy its benefits while minimizing possible health implications.

Table 4. The shortened ultrasonic-assisted osmosis dehydration (UAOD) treatment time at the same solids gain (SG) rate.

Rate of SG (%)	Rate of Shortened Treatment Time (%)
4	51.9
5	55.8
6	56.7
7	58.5
8	60.2
9	61.7

3.3. Effects of Optimum Ultrasonic-Assisted Osmotic Dehydration (UAOD) Treatment Parameters on the Residual Activity of Polyphenol Oxidase (PPO) and Peroxidase

This study showed that the residual activities of both PPO and peroxidase decreased with the increased time of the pickling or UA treatment (Table 5), and there were significant differences for each group ($p < 0.05$). The results of this study were consistent with the findings reported by Bozkir et al. [51], Li et al. [37], and Siucińska et al. [38]. It is worth noting that multiple frequency UA significantly reduces PPO and peroxidase by increasing cavitation and mechanical stress, while highly porous materials provide similar results [20]. The authors have also reported that the highly porous ones produced commensurate results. Specifically, the inactivation of enzymes by UA can be attributed to creating micro-jets or micro-flows that disrupt polypeptide van der Waals interactions and hydrogen bonding interactions within the peptide [14,26]. The generation of free radicals can react with the enzymes' disulfide bonding, leading to structural disruption. However, when using a 20% cane sugar osmotic solution, the inactivation of PPO and peroxidase has been observed in the ginger slices [14], which agreed with the findings of this study. During the same treatment time, there were no great value (PPO and peroxidase) differences between the control and UAOD-treated groups. This was attributed to the sugar barrier on the surface of the food matrix, which prevented the transfer of bioactive compounds [9]. Despite this, Xu et al. [52] reported that strawberry juice was markedly suppressed by multi-frequency power thermo sonication treatments (60 °C/5 min and 55 °C/15 min), and PPO activity was significantly inhibited. It was hypothesized that these differences could be attributed to differences in temperature, as the optimum UAOD process temperature for this study was maintained at 24 ± 1 °C. This tendency remarkably improves the water transfer within the products, although the status of products, added sugar, SG, or heat affect these bioactive contents [9,11,50,52,53]. Khuwijitjaru et al. [46] also reported that prolonged frozen storage (−24 °C) contributed to the reduction in PPO activity.

Table 5. Effects of optimum ultrasonic-assisted osmotic dehydration (UAOD) treatment parameters on the residual activity of polyphenol oxidase (PPO) and peroxidase.

	Control					UAOD				
						Multiple Frequencies (40/80 kHz), an Output Power of 450 W at 45 °Brix Sugar Osmotic Solution				
Time (min)	**5**	**10**	**15**	**20**	**25**	**5**	**10**	**15**	**20**	**25**
Polyphenol oxidase (%)	90.40 ± 3.60 ^{a}	86.40 ± 3.40 ^{a}	84.00 ± 3.30 ^{b}	78.30 ± 1.70 ^{c}	63.20 ± 2.30 ^{d}	92.40 ± 0.80 ^{a}	91.10 ± 0.60 ^{a}	86.10 ± 0.90 ^{a}	81.70 ± 0.80 ^{bc}	63.80 ± 1.00 ^{d}
Peroxidase (%)	85.40 ± 2.20 ^{a}	77.50 ± 1.60 ^{c}	73.20 ± 1.50 ^{c}	66.50 ± 1.50 ^{d}	55.40 ± 2.90 ^{e}	87.00 ± 2.00 ^{a}	74.30 ± 1.70 ^{c}	70.50 ± 2.30 ^{c}	65.60 ± 1.80 ^{d}	60.70 ± 1.10 ^{d}

The different superscript lowercase letters in the same row represent the significant differences ($p < 0.05$).

Moreover, the presence of free radicals can lead to the oxidation of specific amino acids, including tryptophan, histidine, cysteine, and tyrosine, which cause a reduction in enzyme activity [54]. According to reports, the prolonged exposure of PPO and peroxidase enzymes to sudden and intense high temperatures can dissociate their prosthetic group while leading to consequential conformational changes in their secondary and tertiary structures [14,26,55]. Namely, it was attributed to phenomena caused by UA waves' physicochemical and thermal effects [14]. Moreover, the combination of attributes that UA embodies has the potential to efficiently clean agricultural products, which may lead to a reduction in pesticide residues [56]. This information is worth considering while examining UA's viability as a potential solution in future work.

Therefore, the previous results demonstrate the significance of considering the impact of pressure and temperature and the combined effect of UA in achieving effective enzyme inactivation [14]. Customizing these parameters requires meticulous attention to detail to ensure the desired outcome in practical applications.

4. Conclusions

This study suggested that the optimal conditions for treating pineapple with UAOD include multiple frequencies (40/80 kHz), an output power of 450 W, a processing time of 25 min, and a sucrose osmotic solution with 45 °Brix. Namely, implementing these conditions can significantly enhance the efficiency of the SG rate, resulting in a reduction in process duration. Despite high sugar concentrations, the sound pressure performance was less depressed due to the compensatory effect of the multiple frequencies. This effectively reduced the processing time required to achieve the desired level. The efficacy of this approach in mitigating the activity of endogenous enzymes associated with enzymatic browning was experimentally validated. Due to the limitations of this study, further consideration is required to account for variations in other physicochemical characteristics, such as the growth of microorganisms or the presence of pesticide residues and nutrients. It may be advantageous to incorporate health claims when evaluating the impact of sugar reduction on the UAOD pineapple, thereby elevating the product's value level. This study contributes to the economic efficiency of the process, making it a promising approach for treating pineapple with UAOD compared to the traditional method's high sugar concentrations and lengthy processing time. It also provides valuable insights and prospects for advancement in the dried fruit or conserves processing industries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr12061109/s1, Table S1. Changes in different medias' viscosities at different temperatures.

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