applied sciences

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Physicochemical and Microbial Quality of Prepackaged Shrimp Processed by a Scaled-Up Microwave-Assisted Induction Heating Technology

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Abstract: A second generation and scaled-up equipment, named Aligo-2^{TM} (microwave-assisted induction heating, MAIH) with a sample capacity of approximately 1.0 L was designed and invented by Bottle Top Machinery Co., Ltd., Taiwan. Pre-packaged raw shrimps were heated in a scaled-up system using heating temperatures of 130 °C and 90 °C for 80 to 150 s, and the physicochemical and microbial qualities were evaluated. The total plate count, psychrotrophic bacteria count, and coliform levels decreased as heating time increased, whereas the cooking loss, color (L^*, a^*, and W) value, and texture increased. When shrimps were heated for the longest time of 120 s at 130 °C or 150 s at 90 °C, they displayed obvious overcooked, shrunken, and dry appearance. To obtain samples that showed a red color, cooked well, and had no microbial count, better heating conditions for the processing of pre-packaged shrimps via the MAIH scale-up system were 130 °C for 100 s or 90 °C for 130 s. This novel and scaled-up MAIH equipment provides shrimp to be cooked after being packed, thereof avoiding the post-contamination problem.

Keywords: white shrimp; quality; scaled-up microwave-assisted induction heating; thermal processing; prepackaged shrimp

Citation: Hwang, C.-C.; Lin, C.-S.; Lee, Y.-C.; Wei, C.-I.; Tung, H.-N.; Ou, T.-Y.; Chen, T.-Y.; Tsai, Y.-H. Physicochemical and Microbial Quality of Prepackaged Shrimp Processed by a Scaled-Up Microwave-Assisted Induction Heating Technology. *Appl. Sci.* **2021**, *11*, 9514. https://doi.org/10.3390/app11209514

Academic Editor: Monika Sujka

Received: 29 September 2021
Accepted: 11 October 2021
Published: 13 October 2021

1. Introduction

White shrimp (*Litopenaeus vannamei*) is an important crustacean introduced worldwide since the 1970s, and its cultivation has been growing in Asia since 2000 [1]. Its production in Taiwan is approximately 80,000 metric tons annually [2]. White shrimp is an excellent source of several nutrients including peptides, proteins, enzymes, polysaccharides, mineral, and essential amino acids, which can be beneficial for the health of the consumer [2]. Most white shrimp are generally consumed in its cooked form, and in Taiwan, cooking is done largely by boiling in water [2]. Cooking can deactivate polyphenol oxidase and protease, and destroy some pathogens and spoilage bacteria, thereby maintaining the quality of shrimp [3,4].

Microwave (MW) heating has some merits such as a reduced processing time, a fast heating rate, and reduced destruction of nutrients and flavors in food [5]. As MW ovens are usually easy to handle and have a low maintenance cost, MW heating has become popular in the food processing field including for cooking, drying, preservation, and pasteurization of foods [6]. Nevertheless, the non-uniformity of temperature distribution is a primary disadvantage of MW heating, which can often create cold and/or hot spots in the food [7]. The coldest location in food by MW heating can result in serious food safety concerns [8]. Thus, combining MW with other conventional heating methods can effectively overcome the drawbacks of the MW technique [9]. These combinations, namely the MW-assisted (MA) processing technique such as MA-infrared heating, MA-vacuum frying, MA-oven drying, MA-freeze drying, and MA-steam heating, have been widely applied in food processing [9]. In the last few years, an emerging thermal processing technology, MA thermal sterilization (MATS), or MA pasteurization was developed by the research group in Washington State University [10]. In MATS and MA pasteurization, prepackaged food placed in a soft bag is heated in pressurized hot water or MW-heated at a frequency of 915 MHz to perform rapid sterilization or pasteurization, respectively. In particular, the utilization of heated water as an intermediate can overcome the concerns of non-uniform heating and reduce edge heating in food packages by using MW heating [11]. MATS has been used to study the thermal treatments of foods including asparagus, macaroni and cheese, salmon, chicken, mashed potatoes, and sliced beef [7].

In Taiwan, Chang et al. [12] developed an experimental and small scale MA induction heating (MAIH) system consisting of two heating components. In detail, the MW heating unit is in the top half of the machine, whereas the electromagnetic induction heating unit is in the bottom half of the machine. Before heating, the raw food ingredient is put into a heat-resistant container and then sealed with a heat-resistant film. The induction half-cavity consists of tight-fitting top and bottom chambers. The container is first placed in the induction half-cavity and then in the place of induction heating half-cavity and heated by the MAIH system [12]. Recently, this first generation and experimental MAIH was used to cook and pasteurize shrimp for the first time [13]. However, this was small-scale equipment with a sample capacity of approximately 350 mL, which cannot achieve an economical scale. Therefore, the second generation enlarged MAIH machine was designed with a sample capacity of approximately 1.0 L, consistent with the commercial scale (Figure 1).

The purpose of this study was to investigate whether in comparison to the experimental MAIH, the scaled-up MAIH machine could achieve the desirable seafood cooking performance. In addition, to our knowledge, there is no research regarding the application and use of a scaled-up MAIH on heating prepackaged shrimp. Therefore, in this study, a scaled-up MAIH was used for heating prepackaged shrimp, immediately after which the quality attributes of the product including the appearance, color, texture, and microbiological quality were evaluated. This scaled-up MAIH equipment can serve as a potential alternative for developing prepackaged pasteurization processing in commercial prepackaged food.

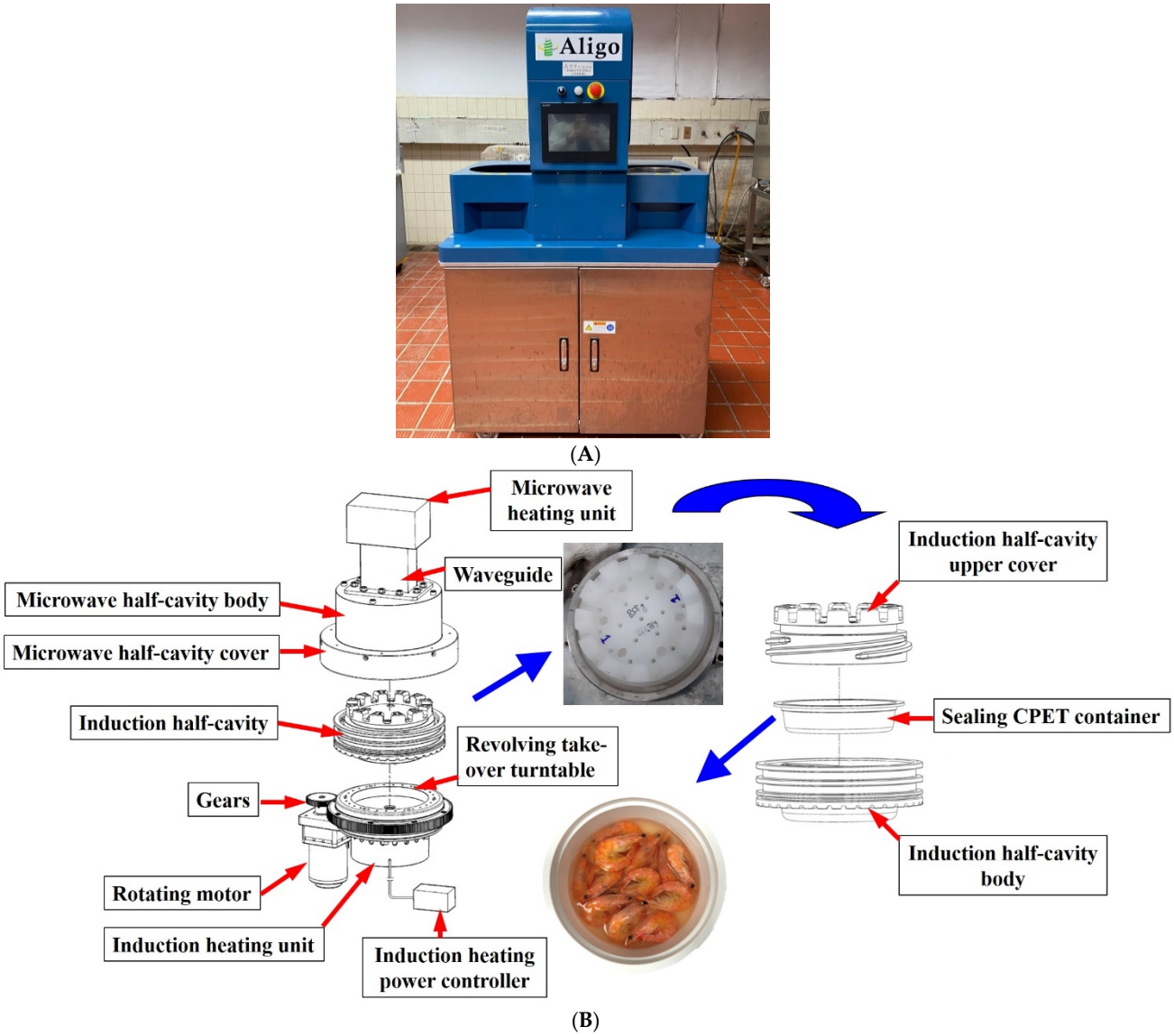


Figure 1. A scaled-up and commercial scale MAIH system-Aligo-2^{TM}, developed and installed at Bottle Top Machinery Co. Ltd., Taiwan. (**A**) Equipment view. (**B**) Schematic diagram.

2. Materials and Methods

2.1. Sample Collection and Treatment

Pacific white shrimps (*Litopenaeus vannamei*) weighing 18–20 g/per shrimp were collected from the seafood market of Kaohsiung in southern Taiwan in September 2019, kept on crushed ice, and transported within 1 h to the Seafood Laboratory, National Kaohsiung University of Science and Technology, Kaohsiung. After arrival, these samples were washed with tap water and then put in a scaled-up crystallized polyethylene terephthalate (CPET) container (17.0 cm i.d. × 6.0 cm height) containing 1% saline being equal to shrimp weight. Each CPET container was filled with 12–14 specimens of shrimp (approximately 250 g). Afterward, the container was sealed using a PET film, and then placed in the induction half-cavity of the MAIH system for heating in the subsequent steps.

2.2. Scaled-Up MAIH Processing

A second generation and scaled-up equipment, named Aligo-2 ^{TM} (MAIH system), with a sample capacity of approximately 1.0 L was designed and invented by Bottle Top Machinery Co. Ltd., Nantou, Taiwan (Figure 1A). The MAIH system comprised two

units including MW in the top half module and induction heating in the bottom half module. Consequently, the top and bottom sections collectively organize this MAIH heating compartment. Before heating, the shrimp CPET container was placed in the induction half-cavity over the induction heating unit (Figure 1B). In the scaled-up MAIH system, the MW heating unit had a power of 1300 W and frequency of 2450 MHz, and the electromagnetic induction heating unit had two heating temperatures of 130 °C and 90 °C (with 1800 W of power). The MAIH heating condition comprised two heating stages, namely combined MW and induction heating in the first stage, and induction heating alone (microwave turned off) in the second stage. At 130 °C, the first stage was maintained for 80 s, and in the second stage, processing time ranged from 0 to 40 s with increments of 10 s each.

Under the heating condition of 90 °C, the first stage was maintained for 100 s, and in the second stage, processing time ranged from 10 to 50 s with increments of 10 s each (Table 1). The heating time design of this scaled-up MAIH study mainly refers to our previous research on experimental MAIH [13]. Our previous study demonstrated that the optimal cooking condition of white shrimp can be achieved by experimental MAIH at 130 °C for 80 s or 90 °C for 100 s [13]. Therefore, in order to reduce the number of repeated heating conditions, the first stage heating time was set to 80 s at 130 °C and 100 s at 90 °C; the second stage heating time (holding time) only gradually increased to determine whether the white shrimp was fully cooked. When the heating finished, the induction half-cavity was taken out from the MAIH equipment and immersed in an ice water bath for 8 min, and then the following measurements were determined in the shrimp samples in the container. Triplicate containers (n = 3) in each heating time condition were taken for analysis.

Table 1. Heating parameters in the scaled-up MAIH equipment for white shrimp treatment.

Temperature	First Stage Heating (s)	Second Stage Heating (s)	Total Heating Time (s)
	MW + IH	IH	
130 °C	80	0	80
	80	10	90
	80	20	100
	80	30	110
	80	40	120
90 °C	100	10	110
	100	20	120
	100	30	130
	100	40	140
	100	50	150

MW + IH: Microwave combined induction heating; IH: Induction heating alone.

2.3. Cooking Loss Measurement

The cooking loss was calculated as the reduction in the shrimp weight after heating, multiplied by 100 [14]. The equation used is as follows:

$$Cooking\ loss\ (\%) = (A - B)/A \times 100 \quad (1)$$

where A is the weight before heating and B is the weight after heating and cooling.

2.4. Microbiological Measurement

With regard to total plate count (TPC), a 25 g sample of shrimp was weighed and moved in a sterilized bottle (including 225 mL of 0.85% sterile saline) for homogenization at 1200 rpm speed for 120 s [3]. Then, 1.0 mL of the stock solution was added into a sterilized test tube containing 9 mL of 0.85% sterile saline for serial dilution. Furthermore, 0.1 mL taken from each dilution was spread on a trypticase soy agar (TSA, Difco, BD,

Sparks, MD, USA) culture medium and incubated at 30 °C for 24–48 h, and the number of colonies on the culture dish was calculated. To determine the psychrotrophic bacteria count (PBC), 0.1 mL of the shrimp homogenate solution and a 10-fold serial dilution solution prepared during the above-mentioned TPC determination was spread on TSA culture medium and incubated at 7 °C for 10 days. Then, the number of colonies on the culture dish was calculated as the PBC [15]. For the determination of coliforms and *Escherichia coli*, 1.0 mL of the shrimp homogenate solution and a 10-fold serial dilution solution prepared during the above-mentioned TPC determination was transferred on Petrifilm EC count plates (3 M Microbiology, St. Paul, MN, USA). After incubating at 35 °C for 24 h, colonies were enumerated according to the manufacturer's guides.

2.5. Appearance and Color Analysis

After heating, the appearance of the shrimp sample was photographed on a white background using a SLR camera (EOS 60D, Canon Inc., Tokyo, Japan) [14]. A colorimeter (CR-300 Chroma Meter, Konica Minolta, Inc., Tokyo, Japan) was used for determining the color change of peeled shrimp meat after the MAIH-treated groups [14]. The colorimeter was first calibrated against standard white (L^* = 96.72, a^* = 0.11, and b^* = −0.14) and red plates (L^* = 51.13, a^* = 50.00, and b^* = 24.03) before measurement. The values of L^* (lightness), a^* (redness), and b^* (yellowness) were recorded, and the average value was obtained by calculations from four replicate measurements at different spots on each sample. The W value (whiteness) of the sample was then calculated as shown below in Equation (2). The final result is expressed as an average value for triplicate peeled shrimps [14].

$$W = 100 - \left[(100 - L*)^2 + a*^2 + b*^2 \right]^{1/2} \quad (2)$$

2.6. Texture Determination

A TA.XT2 Texture Analyzer (Stable Micro System Ltd., Godalming, UK) was used to carry out the textural attributes of peeled shrimp after their treatment under the scaled-up MAIH at 90 °C and 130 °C [14]. Tests for hardness, cohesiveness, springiness, and chewiness were performed in the texture profile analysis. The two-cycle compression test was performed using a TA39 cylinder probe (2 mm diameter, 20 mm length) with a target value of 4.00 mm, predicted speed of 2 mm/s, test and return speeds of 1.5 mm/s, and a 2 g trigger force. The compression rate was 50% of the original height, the pressing depth was 0.5 cm, and the holding time was 3 s. The samples were carefully placed on the support base so that the probe was perpendicular to the peeled shrimp tissue at different locations on the sample. Triplicate individual shrimps (n = 3) were sampled from each heating time with determinations performed at three different locations on each body, while the mean values were recorded.

2.7. Sensory Analysis

To compare the consumer acceptance of the prepackaged shrimps after their treatment under the scaled-up MAIH, sensory evaluations were performed on both the processed samples (MAIH at 130 °C for 100 s and MAIH at 90 °C for 130 s) and shrimps heated using the traditional boiling water method. Regarding samples treated with boiling water, approximately 1000 g of the samples were cooked in a water bath machine (L29.5 × W23.5 × H15 cm) (SB-10, Jaan-Yuh, Taipei, Taiwan) with approximately 3 L of 1% NaCl solution set at 90 °C for 150 s. After heating, the shrimps (100 g) were packed in each sterile whirl-pak bag (Nasco Whirl-Pak Standard Sample Bags, WI, USA) and immersed in water with crushed ice for 6 min. The shrimp samples treated with boiling water and scaled-up MAIH at 130 °C for 100 s and MAIH at 90 °C for 130 s were evaluated using organoleptic analysis via 30 untrained panelists aged between 19 and 25. After heating with the above methods, three shrimp samples were placed on plates coded with random three-digit numbers. The panelists were asked to score their liking with respect to color, flavor, odor, taste, texture, and overall acceptance using the nine-point hedonic scale (9 = like extremely, 7 = like

moderately, 5 = neither like or nor dislike, 3 = dislike moderately, 1 = dislike extremely) [16]. No panelist was allergic to shrimp. They rinsed their mouths with distilled water between testing samples with different code numbers.

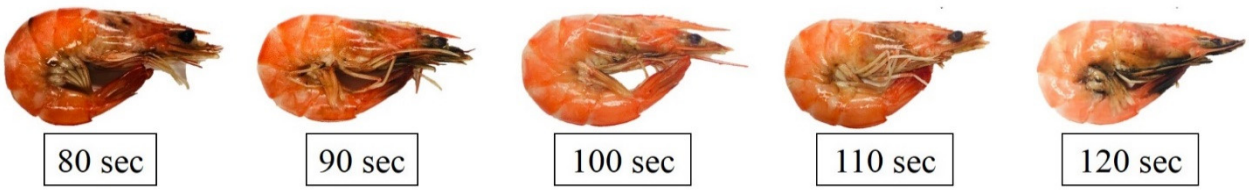
2.8. Statistical Analysis

The package SPSS version 22.0 for Windows (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. The statistics were performed using one-way analysis of variance (ANOVA). Duncan's multiple range test was used to determine data comparisons of the mean in triplicates. A p-value < 0.05 was regarded as statistically significant.

3. Results and Discussion

3.1. Appearance of Shrimp

Figure 2 shows the appearance of the shrimps processed using the scale-up MAIH machine at 130 °C for 80–120 s and at 90 °C for 110–150 s. With treatment under 130 °C for 80 s and 90 s, although the shrimp had a red appearance, a dark brown color could be observed on the head and legs. The results indicated that the samples were undercooked. With heating time extended to 100 s and 110 s, the whole shrimp body displayed a red color and was cooked thoroughly. Nevertheless, heating above 120 s resulted in the shrimp shell changing to a dry and shrunken appearance, indicating that the sample was overcooked (Figure 2A). Similar to 130 °C, after heating at 90 °C for 110 and 120 s, the red appearance was observed, but the dark brown color was still observed on certain parts of the head and legs. The samples were found not to have been heated sufficiently (i.e., undercooked). With heating time extended to 130 s and 140 s, the whole shrimp body displayed a red color and was fully cooked. Nevertheless, heating above 150 s gave the shrimp shell a dry and shrunken appearance, indicating that the sample was overcooked (Figure 2B). The results are consistent with findings of a previous study demonstrating that after heating whole mussels at 90 °C, area shrinkage increased with the increase in heating time [14]. This is because heating results in the denaturation of muscle myosin and protein, and shrinkage of muscle fiber diameter and sarcomere length [14].



(**A**)

(**B**)

Figure 2. Appearance changes of white shrimp using the scaled-up MAIH system set at 130 °C (**A**) and 90 °C (**B**) for various heating times.

3.2. Cooking Loss and Microbial Counts of Shrimp

Table 2 shows the cooking loss in shrimps processed in the scaled-up MAIH machine at 130 °C for 80–120 s and at 90 °C for 110–150 s. At 130 °C, with the increase in heating time, the cooking loss in shrimps increased from 1.16% in the sample at 80 s to 3.66% in the

sample at 120 s. The result indicated that the loss of water released from the shrimp body sped up with extended heating time. As shown in Figure 2A, the cooking loss in the sample heated to 130 °C for 120 s was 3.66%, and resulted in a dry and shrunken appearance. Similarly, with heating at 90 °C, the cooking loss also increased with an increase in heating time from 1.50% at 110 s to 4.39% at 150 s. In addition, as shown in Figure 2B, the cooking loss in the sample heated at 130 °C for 150 s was 4.39%, and the appearance changed to dry and shrunken. However, Erdogdu et al. [17] indicated that the cooking loss in shrimp increased from 15.8% to 28.7% with increasing heating time when heating in boiling water at 90 °C. The higher cooking loss in samples observed by Erdogdu et al. [17] than that in our study is primarily attributed to the longer heating time of above 3 min, and different heating method. Ovissipour et al. [14] demonstrated that the denaturation of muscle protein such as myofibril protein and collagen by the heating process is the key mechanism that causes water loss. In addition, during the thermal process, the shrinkage and hardening of muscle tissue results in increased internal pressure, which further causes the release of water from the meat tissue. Consequently, the shrimp weight decreases after being subjected to the thermal process [18].

Table 2. Changes of cooking loss, total plate count (TPC), psychrotrophic bacteria count (PBC), coliform, and *E. coli* in white shrimp using the scaled-up MAIH system set at 130 °C and 90 °C for various heating times.

Temperatures	Heating Time (s)	Cook Loss (%)	TPC (log CFU/g)	PBC (log CFU/g)	Coliform (log CFU/g)	*E. coli* (log CFU/g)
Raw shrimp		0	4.93 ± 0.23^{a}	3.27 ± 0.11^{a}	2.21 ± 0.14^{a}	<1.0
130 °C	80	1.16 ± 0.12^{e}	3.45 ± 0.52^{b}	2.88 ± 0.32^{b}	1.68 ± 0.19^{b}	<1.0
	90	2.41 ± 0.29^{d}	3.26 ± 0.39^{b}	2.17 ± 0.27^{c}	<1.0 ^{c}	<1.0
	100	3.45 ± 0.11^{c}	<2.0 ^{d}	<2.0 ^{d}	<1.0 ^{c}	<1.0
	110	3.50 ± 0.15^{c}	<2.0 ^{d}	<2.0 ^{d}	<1.0 ^{c}	<1.0
	120	3.66 ± 0.18^{b}	<2.0 ^{d}	<2.0 ^{d}	<1.0 ^{c}	<1.0
90 °C	110	1.50 ± 0.28^{e}	2.81 ± 0.38^{c}	2.54 ± 0.29^{bc}	1.26 ± 0.42^{b}	<1.0
	120	2.05 ± 0.33^{d}	2.45 ± 0.05^{c}	2.05 ± 0.25^{c}	<1.0 ^{c}	<1.0
	130	2.73 ± 0.19^{cd}	<2.0 ^{d}	<2.0 ^{d}	<1.0 ^{c}	<1.0
	140	3.46 ± 0.24^{c}	<2.0 ^{d}	<2.0 ^{d}	<1.0 ^{c}	<1.0
	150	4.39 ± 0.11^{a}	<2.0 ^{d}	<2.0 ^{d}	<1.0 ^{c}	<1.0

Each value represents the average ± standard deviation of three replicates; different lowercase letters indicate significant differences in the same column ($p < 0.05$).

Table 2 also presents the counts of TPC, PBC, coliform, and *E. coli* in shrimps treated using the scaled-up MAIH machine at 130 °C for 80–120 s and at 90 °C for 110–150 s. The initial TPC and PBC of raw shrimp were 4.93 log CFU/g and 3.27 log CFU/g, respectively. With heating at 130 °C, the TPC and PBC levels decreased significantly ($p < 0.05$) with an increase in heating time, and after heating for 100 s to 120 s, TPC and PBC levels were undetected (<2.0 log CFU/g). Similarly, the TPC and PBC levels decreased significantly with an increase in heating time with heating at 90 °C, and at heating times above 130 s, none of these samples showed detectable TPC and PBC levels (<2.0 log CFU/g) (Table 2). This suggests that a high heating time with the MAIH at 130 °C or 90 °C is effective in reducing the TPC and PBC levels in shrimp. Both the TPC and PBC are important indexes for evaluating the quality of fresh and low-temperature-stored aquatic products. A similar result was previously demonstrated by Sae-leaw et al. [3], who found that boiling water until the core temperature of the shrimp reached 70 °C and holding for 30 s significantly reduced the TPC and PBC levels in white shrimp to 2.25 log CFU/g and 1.0 log CFU/g, respectively.

Regarding the coliform count, the initial coliform count of raw shrimp was 2.21 log CFU/g (Table 2). After the samples were processed using the scaled-up MAIH at 130 °C for 80 s and 90 °C for 110 s, the coliform count was 1.68 and 1.26 log CFU/g, respectively. No

coliforms (<1.0 log CFU/g) were found in the other MAIH-heated samples with extended heating time. However, *E. coli* was not detected in any of the raw or heated shrimp samples (Table 2). This indicates that the scaled-up MAIH at 130 °C for 90 s or 90 °C for 120 s was the least effective in reducing coliform count in shrimp. In summary, when the heating condition of the MAIH was set at 130 °C for 100 s or 90 °C for 130 s, the scaled-up MAIH method was able to provide effective pasteurization of prepackaged shrimp.

3.3. Color Values of Shrimp

The changes in color-related values (L^*, a^*, b^*, and W) of peeled shrimps processed by a scaled-up MAIH machine at 130 °C for 80–120 s and at 90 °C for 110–150 s are shown in Table 3. The raw shrimp body had an L^*, a^*, b^*, and W of 25.23, 1.90, −1.06, and 25.20, respectively. After the shrimp was processed by scaled-up MAIH under 130 °C, the L^* (lightness) values increased significantly from 51.78 in the 80 s sample to 58.09 in the 120 s sample ($p < 0.05$). Similar to 130 °C, heating of samples at 90 °C increased the L^* values from 52.79 in the 110 s sample to 55.66 in the 150 s sample ($p < 0.05$). The increase in lightness is because of the decrease in pigment activity and protein coagulation (denaturation), because protein coagulation changes the characteristics of the sample surface, increases light reflection, and produces a white appearance [19]. Furthermore, after heating at 130 °C, the a^* value (redness) of samples increased significantly, from 6.79 in the 80 s sample to 8.82 in the 120 s sample of ($p < 0.05$), whereas that of samples heated at 90 °C increased from 6.86 in the 110 s sample to 8.69 in the 150 s sample ($p < 0.05$). When alive, the body surface of crabs and shrimps shows a brown or dark brown color. This color is because of a protein known as crustacyanin, which contains a red pigment (i.e., astaxanthin). During the thermal process, this protein is denatured and releases astaxanthin (red pigment), which alters the color of the body surface to red [20]. In contrast, the b^* value (yellowness) had the opposite trend, which decreased with an increase in heating time and reached the lowest value of −2.29 with heating at 130 °C for 120 s, and −2.30 with heating at 90 °C for 150 s. In addition, W (whiteness) values of the samples heated at 130 °C increased from 51.51 in the 110 s sample to 57.48 in the 120 s sample, whereas that of the samples heated at 90 °C tended to increase significantly ($p < 0.05$) to 55.24 for the 150 s sample with increased heating time (Table 3). It was found that the color of peeled shrimp turns increasingly white with the increase in heating time, which may be because of the denaturation and degeneration of proteins (e.g., myofibrillar and sarcoplasmic proteins), and the whitening phase is accompanied with the production of the cooked seafood flesh [18].

Table 3. Values of color (L^*, a^*, b^*, W) in peeled white shrimp using the scaled-up MAIH system set at 130 °C and 90 °C for various heating times.

Treatments	Heating Time (s)	L^*	a^*	b^*	W
Peeled raw shrimp		25.23 ± 0.60^{e}	1.90 ± 0.12^{d}	-1.06 ± 0.04^{a}	25.20 ± 0.58^{d}
130 °C	80	51.78 ± 0.52^{d}	6.79 ± 0.22^{c}	-1.86 ± 0.17^{b}	51.51 ± 0.38^{c}
	90	52.63 ± 0.83^{d}	7.96 ± 0.32^{b}	-1.77 ± 0.16^{b}	52.22 ± 0.63^{c}
	100	52.65 ± 0.77^{d}	8.53 ± 0.25^{a}	-1.87 ± 0.28^{b}	52.17 ± 0.52^{c}
	110	56.04 ± 0.65^{b}	8.62 ± 0.40^{a}	-2.03 ± 0.52^{bc}	55.50 ± 0.55^{b}
	120	58.09 ± 0.91^{a}	8.82 ± 0.39^{a}	-2.29 ± 0.37^{cd}	57.48 ± 0.50^{a}
90 °C	110	52.79 ± 0.66^{d}	6.86 ± 0.18^{c}	-1.92 ± 0.61^{bc}	51.66 ± 0.54^{c}
	120	52.39 ± 1.01^{d}	8.12 ± 0.09^{b}	-1.99 ± 0.25^{bc}	52.26 ± 0.65^{c}
	130	54.96 ± 0.76^{c}	8.18 ± 0.13^{b}	-2.02 ± 0.26^{bc}	54.18 ± 0.40^{bc}
	140	54.06 ± 0.96^{c}	8.57 ± 0.30^{a}	-2.12 ± 0.17^{cd}	53.22 ± 0.71^{bc}
	150	55.66 ± 0.75^{b}	8.69 ± 0.23^{a}	-2.30 ± 0.22^{cd}	55.24 ± 0.53^{b}

Each value represents the average ± standard deviation of three replicates; different lowercase letters indicate significant differences in the same column ($p < 0.05$).

Overall, these results indicate that the color values (L^*, a^*, and W) in peeled shrimp meat after processing at the scaled-up MAIH under 130 °C and 90 °C increased with increased heating time. Compared to its appearance in Figure 2, when the heating condition of scaled-up MAIH was set at 130 °C for 100 s or 90 °C for 130 s, the shrimp was cooked well and had a fully red appearance.

3.4. Texture Properties of Shrimp

Table 4 presents the texture properties of peeled shrimps processed by the scaled-up MAIH machine at 130 °C for 80–120 s and at 90 °C for 110–150 s. The raw shrimp meat had a hardness of 101.2 (g). After heating at the scaled-up MAIH under 130 °C or 90 °C, the hardness of shrimp samples increased significantly with increased heating time, and reached the highest level of 295.9 (g) at 130 °C and 120 s and 299.6 (g) at 90 °C and 150 s. The increase in the hardness of shrimp samples under heating may be related to the denaturation and aggregation of myofibrillar protein that reduces water holding capacity and shrinks muscle fibers, subsequently leading to a hard and compact tissue texture [14,18]. The cohesiveness increased from 0.22 in the raw shrimp meat to 0.70 at 130 °C and 120 s and 0.69 at 90 °C and 150 s with an increase in heating time ($p < 0.05$). The springiness of initial raw shrimp was detected as approximately 5.08 (mm). Although the mean springiness in all heated samples decreased slightly with increasing heating time, there was no significant difference between these and the raw sample ($p > 0.05$). Similar results with hardness were observed for chewiness, increasing from 5.90 (mJ) in the raw shrimp to 11.05 (mJ) at 130 °C and 120 s and 11.50 (mJ) at 90 °C and 150 s ($p < 0.05$) in the cooked shrimp. Overall, the average values of hardness, cohesiveness, and chewiness in the heated shrimps increased with an increase in heating time. The results of this study are similar to those of a previous report, in which the texture (e.g., hardness) of the Pacific chum salmon (*Oncorhynchus keta*) tended to rise with increased heating time and temperature, after hydrothermal processing [21]. After heating, it is assumed that the changes in tissue texture are because of the denaturation and aggregation of the muscle protein at a high temperature, which causes tissue structure shrinkage and water release from the shrimp body [14,18].

Table 4. Values of texture properties in peeled white shrimp using the scaled-up MAIH system set at 130 °C and 90 °C for various heating times.

Temperatures	Heating Time (s)	Hardness (g)	Cohesiveness	Springiness (mm)	Chewiness (mJ)
Peeled raw shrimp		101.2 ± 2.60 ^{e}	0.22 ± 0.01 ^{e}	5.08 ± 0.04 ^{a}	5.90 ± 0.61 ^{c}
130 °C	80	250.7 ± 20.2 ^{c}	0.54 ± 0.02 ^{c}	5.00 ± 0.21 ^{a}	8.01 ± 0.83 ^{b}
	90	275.6 ± 23.8 ^{bc}	0.58 ± 0.04 ^{b}	5.02 ± 0.16 ^{a}	8.80 ± 0.93 ^{b}
	100	271.5 ± 11.7 ^{bc}	0.63 ± 0.03 ^{b}	5.01 ± 0.26 ^{a}	9.79 ± 0.95 ^{ab}
	110	289.4 ± 20.5 ^{ab}	0.65 ± 0.04 ^{ab}	5.23 ± 0.29 ^{a}	10.21 ± 0.88 ^{a}
	120	295.9 ± 15.9 ^{a}	0.70 ± 0.03 ^{a}	5.20 ± 0.19 ^{a}	11.05 ± 0.90 ^{a}
90 °C	110	210.9 ± 17.6 ^{d}	0.38 ± 0.03 ^{d}	4.95 ± 0.21 ^{a}	8.06 ± 1.04 ^{b}
	120	249.3 ± 19.1 ^{c}	0.56 ± 0.01 ^{bc}	5.01 ± 0.25 ^{a}	9.76 ± 0.69 ^{ab}
	130	260.6 ± 25.1 ^{bc}	0.60 ± 0.05 ^{b}	5.02 ± 0.26 ^{a}	10.01 ± 1.00 ^{ab}
	140	274.6 ± 21.6 ^{ab}	0.67 ± 0.02 ^{ab}	5.10 ± 0.17 ^{a}	10.95 ± 0.78 ^{a}
	150	299.6 ± 30.7 ^{a}	0.69 ± 0.04 ^{a}	5.15 ± 0.12 ^{a}	11.50 ± 0.99 ^{a}

Each value represents the average ± standard deviation of three replicates; different lowercase letters indicate significant differences in the same column ($p < 0.05$).

3.5. Sensory Attributes

Table 5 shows the sensory analysis provided by the 30 panelists of the shrimps heated via boiling water, MAIH at 130 °C, and MAIH at 90 °C. Regarding color and odor, although the mean scores of the MAIH samples were higher than those of the boiling water samples, no statistical differences ($p > 0.05$) were observed between the three samples. In

general, there were no significant differences ($p > 0.05$) in flavor, taste, and texture among the samples, with samples receiving scores ranging from 6.58 to 6.84, 6.78 to 6.94, and 6.93 to 6.96, respectively. Similarly, no significant difference ($p > 0.05$) was found among the three samples in overall acceptance. Therefore, sensory analysis showed that the shrimp samples heated by a scaled-up MAIH machine set at 130 °C for 100 s or 90 °C for 130 s had a organoleptic property similar to that of the sample heated by conventional boiling water.

Table 5. Organoleptic analysis of shrimp samples heated in boiling water at 90 °C for 150 s, scaled-up MAIH at 130 °C for 100 s, and scaled-up MAIH at 90 °C for 130 s.

Treatments	Color	Flavor	Odor	Taste	Texture	Overall Acceptance
Boiling water	7.24 ± 1.24 [a]	6.68 ± 1.20 [a]	7.10 ± 0.69 [a]	6.85 ± 1.50 [a]	6.94 ± 1.37 [a]	7.02 ± 1.16 [a]
MAIH 130 °C	7.50 ± 1.11 [a]	6.84 ± 1.35 [a]	7.31 ± 0.99 [a]	6.78 ± 1.22 [a]	6.93 ± 1.06 [a]	7.06 ± 1.04 [a]
MAIH 90 °C	7.38 ± 1.31 [a]	6.58 ± 1.24 [a]	7.26 ± 0.74 [a]	6.94 ± 1.01 [a]	6.96 ± 0.87 [a]	7.03 ± 1.35 [a]

Each value represents the average ± standard deviation ($n = 30$); different lowercase letters indicate significant differences in the same column ($p < 0.05$).

As shown in the results described above, the better heating time for white shrimp after MAIH is one that produces the completely red color and no microbial count, and results in few changes in cooking loss and surface shrinkage. Therefore, the shrimp samples after heating in the scaled-up MAIH at 130 °C for 100 s, or at 90 °C for 130 s achieved a better appearance, and had a better microbiological quality; in addition, the lower cooking loss and surface shrinkage were observed in these samples. Recently, a previous research also reported that after shrimps processed by MAIH heating, the temperature of all samples in the CPET container was within the range of 90–100 °C as a result of the measurement by the thermal imaging method, indicating that these heated shrimps were suffered by uniform heating by way of uniform temperature distribution [22]. In this study, the commercial and scaled-up MAIH equipment composed of MW and induction heating is an emerging and simple technology for prepackaged shrimp processing. In the future, new research on this scaled-up MAIH is required to study the storage life of prepackaged white shrimp after heating using a MAIH.

4. Conclusions

In this study, the heating effect of a scaled-up MAIH system on the physicochemical and microbial qualities of white shrimp was observed. The results showed that the shrimps processed with the MAIH at 130 °C for 100 s or at 90 °C for 130 s were effective in reducing microbial counts to a nondetectable level. However, the longer heating time led to deleterious effects, which showed in the high cooking loss, surface shrinkage, and dry appearance. Therefore, these findings indicate that better pasteurization and cooking condition under the MAIH system cause minimum negative effects to shrimp appearance and cooking loss when heated at 130 °C for 100 s or at 90 °C for 130 s. A novel and scaled-up thermal technique, MAIH, for prepackaged shrimp, could provide some advantages such as fast heating rate and the capability to cook and pasteurize simultaneously.

Author Contributions: Conceptualization, C.-S.L., Y.-C.L. and Y.-H.T.; Methodology, Y.-H.T., Y.-C.L. and C.-C.H.; Analysis, C.-C.H. and C.-S.L.; Data curation, C.-S.L., C.-C.H. and T.-Y.O.; Writing—original draft preparation, Y.-C.L. and C.-C.H.; Writing—review and editing, C.-S.L. and Y.-H.T.; Supervision, C.-I.W. and H.-N.T.; project administration, T.-Y.O., C.-I.W. and H.-N.T.; Funding acquisition, T.-Y.O., Y.-C.L. and T.-Y.C.; Validation, T.-Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the support of the marine characteristic cross-campus research project (110G01) and higher education sprout project (110E9010BA02) of the National Kaohsiung University of Science and Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical reasons.

Acknowledgments: We also thank Ya-Chun Yu and Jung-Kuei Hsieh to provide the MAIH facilities.

Conflicts of Interest: All authors declare no conflict of interest in the publication of this paper.

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