Research Article
Journal of Advanced Development in Engineering and Science
Vol.16 ● No.46 • May – August 2026

Development of a Ready-to-Eat Puffed Snack from Salmon Skin Using a Multi-Stage Hot-Air and Microwave Drying Process

Pitipat Bootkote[1], Suwit Paengkanya[2], Krit Apinyavisit[3], Patiwat Khomwachirakul[3] and Ponlakrit Kumklam[4*]

Received: 23 February 2026
Revised: 24 August 2026
Accepted: 26 August 2026

ABSTRACT

Creating puffed snacks from protein-rich byproducts like salmon skin poses challenges in balancing drying efficiency, energy consumption, and product quality. This research focused on developing a ready-to-eat puffed snack using salmon skin through a multi-stage drying technique. The process involved initially drying the skins with hot air at 90 °C, followed by microwave puffing, and then returning them to hot-air drying until the moisture content fell below 4% (d.b.). The study examined how varying microwave power and puffing duration influenced drying rates, product quality, and energy use. Results showed that increasing microwave power and puffing time significantly reducedtotal drying time. This improvement was due to intense steam generation creating a porous microstructure, which enhanced the snacks' texture by reducing hardness and increasing crispiness. Though more intense processing led to darker products from non-enzymatic browning.The 800 W microwave treatment with 5 minutes of puffing achieved the lowest specific energy consumption at 577.10 MJ/kgH_2O.

Keywords: Salmon Skin; Microwave Puffing; Hot-air Drying; Ready-to-eat Snack; Texture

[1]Division of Modern Agricultural Engineering, Faculty of Agriculture, Rajamangala University of Technology Srivijaya, Nakhon Si Thammarat, Thailand 80110
[2]Division of Sustainable Industrial Management Engineering, Faculty of Engineering, Rajamangala University of Technology Phra Nakhon, Bangkok, Thailand 10800
[3]Division of Machanical Engineering, Faculty of Engineering, Rajamangala University of Technology Phra Nakhon, Bangkok, Thailand 10800
[4]Division of Industrial Materials Science, Faculty of Science and Technology, Rajamangala University of Technology Phra Nakhon, Bangkok, Thailand 10800
*Corresponding author e-mail: ponlakrit.k@rmutp.ac.th

Introduction

The global aquaculture sector plays a vital role in ensuring food security, with salmonid production being a significant and rapidly growing segment. Global Atlantic salmon production is set to rebound significantly in 2025, reaching around 1.4 million metric tons in the first half of the year. This marks a 13.6 percent increase compared to the same period in 2024 [1]. However, the industrial filleting of salmon generates substantial by-products, with the skin alone constituting approximately 5–7% of the fish's live weight. This by-product is notably rich in high-value nutrients, especially marine collagen and long-chain omega-3 fatty acids, which are scientifically recognized for their beneficial effects on skin health, joint integrity, and cardiovascular function. Despite this nutritional potential, a considerable proportion of fish processing by-products, estimated to be over 60% are underutilized, often diverted into low-value applications such as animal feed or disposed of as waste.[2] This not only represents a significant loss of valuable bio-resources but also contributes to environmental challenges, highlighting an urgent need for innovative strategies to promote a more sustainable and circular bio-economy.

At the same time, the market for ready-to-eat (RTE) foods is expanding rapidly, driven by evolving consumer lifestyles that prioritize convenience, health, and sustainability. Although the health benefits of seafood are a primary driver of consumption, the lack of diverse and appealing RTE fish products remains a significant barrier in the market. This gap presents a compelling opportunity to transform underutilized salmon skin into a high-value, nutritious, and convenient snack, which aligns with consumer trends and helps reduce waste.

Puffing technology is widely used to create appealing, crispy-textured RTE snacks. However, traditional methods have notable drawbacks. For instance, deep-fat frying can increase the fat content of the final product to 35–45%.[3] Alternative technologies, such as air frying and infrared radiation, offer heating rates that are up to 30% faster than conventional methods.[4]Recent studies have explored various drying approaches for fish skin, including hot-air drying of salmon skin [5, 6], which demonstrated the influence of temperature on gelatin denaturation. Microwave drying of fish skin effectively reduced drying time while preserving nutritional quality. Higher microwave power decreased water activity and whiteness, with elasticity, hardness, and rehydration rate initially increasing before declining. However, the application of combined multi-stage HA-MW drying specifically for salmon skin puffing remains largely unexplored. Currently, the optimal puffing method for creating a high-quality snack from salmon skin has not yet been established.

Microwave (MW) assisted puffing has emerged as a promising alternative due to its volumetric heating mechanism, which generates rapid internal steam pressure and facilitates efficient moisture removal. Numerous studies have shown that MW power and exposure time significantly influence drying kinetics, product microstructure, texture, color, and energy

efficiency across various food matrices. Paengkanya et al. [7] investigated MW-assisted drying of durian chips and reported that increasing MW power from 150 W to 250 W reduced total drying time by approximately 70%. This acceleration was attributed to enhanced internal steam generation, which created a porous microstructure, reduced hardness around 40%, and increased crispiness compared with hot air (HA) drying. Similarly, Liang et al. [8] examined MW drying of pork chip snacks at MW intensities of 2-6 W/g (pork) and found that brittleness increased with drying time up to 22 minutes but then decreased at 23–24 minutes. Their scanning electron microscopy (SEM) analysis confirmed that numerous large pores promoted brittleness.

Puffing duration is a key processing variable that significantly affects the final attributes of puffed snack products. The length of exposure to puffing energy directly determines the degree of structural expansion and the consequent textural characteristics. Insufficient puffing time often leads to incomplete expansion and a dense, underdeveloped product matrix. Conversely, excessive puffing time may cause over-expansion, resulting in structural collapse, increased fragility, or loss of the desired crispy texture [9, 10]. The influence of MW power on the physicochemical and sensory properties of various cracker types has been documented. For instance, research on fish-based crackers, crackers incorporating seaweed and kale, along with shrimp crackers, has demonstrated that MW power levels play a significant role in determining product expansion, color development, and texture [11, 12]. These findings collectively underscore the importance of optimizing both power and time parameters to achieve desirable product quality in MW-puffed snacks.

Despite the substantial evidence supporting MW-assisted drying for various food products, there has been limited research systematically investigating its application to salmon skin. Salmon skin has unique compositional characteristics, particularly a high collagen content and distinct dielectric properties, which set it apart from the commonly studied materials. These properties can significantly impact drying kinetics and the final quality of the product. Therefore, this study aimed to examine the effects of MW power and puffing time on drying kinetics, as well as the physicochemical properties (color, texture, microstructure) and energy consumption during multi-stage drying of salmon skin. The findings will provide valuable insights for developing a high-quality, shelf-stable puffed snack from this underutilized aquaculture byproduct.

Materials and Methods

Sample Preparation

Salmon (*Salmo salar*) skins were sourced from a commercial supplier, Orange Fish Shop, located in Bangkok, Thailand. Upon arrival, the skins were manually processed to remove scales and any residual adipose tissue using a scalpel. Next, they were washed in a 1.0% (w/v)

sodium chloride solution for 5 minutes (this process was repeated twice) to eliminate surface impurities. This was followed by four rinses, each lasting 5 minutes, in distilled water to remove any remaining salt and ensure a neutral odor. The cleaned skins were then patted dry and cut into uniform strips measuring 5 cm by 2 cm using a precision cutter in preparation for subsequent drying experiments.

Hot-Air Drying System

Drying experiments were conducted using a custom-designed HA dryer (see Fig. 1). The system featured a drying chamber with internal dimensions of 0.52 m (W) × 0.52 m (L) × 0.52 m (H). Ambient air was drawn into the system by a blower connected to a 2.2 kW motor and heated to the desired temperature by a 3 kW electrical heater. The heated air was directed through the chamber, passing over samples placed on perforated trays before being partially exhausted. To enhance energy efficiency, approximately 80% of the exhaust air was recirculated back into the chamber through an adjustable valve and damper system.

Multi-Stage Drying and Puffing Protocol

A three-stage combined drying process was utilized in the study. Before each experiment, the dryer was preheated to ensure a stable chamber temperature. In stage 1, the salmon skin strips were dried using HA at 90 °C, with an air velocity of 0.3 m/s, until the moisture content reached an intermediate level of 10% (d.b.). In stage 2, the partially dried samples were subjected to MW puffing in a domestic microwave oven (Samsung, Model MG23F301EAS, Thailand). The MW power levels were set to 450, 600, and 800 W, with durations of 1, 3, and 5 minutes. Finally, in stage 3, the puffed samples were returned to the HA dryer at 90 °C for final drying until the moisture content fell below 4% (d.b.). The chamber temperature was controlled using a PID controller. Sample weight was monitored with a digital balance (Sartorius, model CP3202S, Germany; accuracy ±0.01 g), and the surface temperature of the product was measured intermittently with an infrared thermometer (Shinko, Model IRT-100-TA, Japan; accuracy ±2 °C).

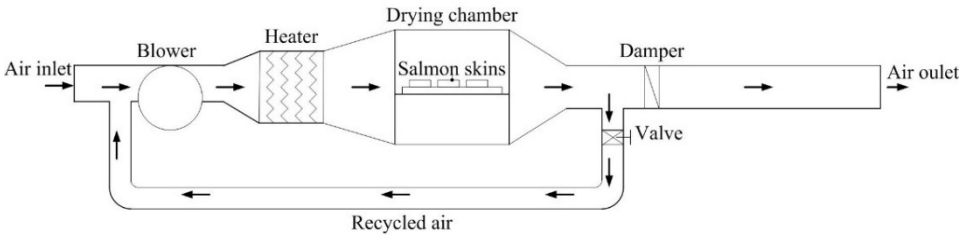


Figure 1 Schematic diagram of the hot-air dryer.

Moisture content determination

The initial moisture content of the raw salmon skin was measured to be between 270% and 300% (d.b.) using the standard AOAC method [13]. This was done by drying triplicate samples in a hot-air oven (Memmert, Model UF75, Germany) at 105 °C for 24 hours. To establish drying curves, the moisture content at various stages of the multi-stage process was determined using the same method.

Energy consumption determination

A kilowatt-hour meter (DAI-ICHI, DD28, Thailand) was used to measure the total energy consumption for each drying treatment. The specific energy consumption (SEC) was calculated based on the total energy used during the drying process in relation to the total amount of moisture evaporated. This relationship can be expressed with the following equation:

$$SEC_{Total} = \frac{2.6(E_{Blower} + E_{MW}) + E_{Heater}}{M_{w}} \quad (1)$$

where SEC_{Total} is the total specific energy consumption (MJ/kgH_2O), E_{Blower} is the electrical energy consumed by the blower (MJ), E_{MW} is the electrical energy supplied to the magnetron radiator for microwave in puffing process (MJ), E_{heater} is the energy required by the electric heater to raise the ambient air temperature to the desired level (MJ), and M_w is the total amount of evaporated water (kg). To allow fair comparisons of energy carriers and accurately reflect industrial efficiency, a primary energy conversion multiplier of 2.6 is incorporated, accounting for cumulative losses in the electricity supply chain [14,15]. All meter readings in kWh are converted to MJ using a standard conversion factor of 3.6 MJ per kWh for consistency in units.

Color Measurement

The color of the dried salmon skin was quantified using a spectrophotometer (Konica Minolta, CM-3500d, Japan) equipped with a D65 illuminant and an observer angle of 10°. The color was described according to the CIE color system. The instrument was calibrated with a standard white plate (L^* = 93.19, a^* = -1.12, b^* = 1.33). In this system, L^* represents lightness or darkness, a^* indicates redness or greenness, and b^* reflects yellowness or blueness of the sample. Color measurements were taken on both sides of ten randomly selected strips from each batch, and the average values were reported.

Microstructure Analysis

The internal microstructure of the dried samples was examined using a Scanning Electron Microscope (SEM, JEOL, Model JSM-5410 LV, Tokyo, Japan). To preserve the native structure and remove surface oil, samples were cryo-fractured after immersion in liquid nitrogen for 30 minutes. The cross-sections were sputter-coated with a thin layer of gold and observed at an acceleration voltage of 15 kV with a 40x magnification.

Texture Profile Analysis

The textural properties of the dried skins, specifically hardness and crispiness (number of peaks), were determined with a Texture Analyzer (Stable Micro Systems, Model TA.XT. Plus, Surrey, UK). A puncture test was performed using a cylindrical probe (HDP/BSK) with the following parameters: pre-test speed of 1 mm/s, test speed of 2 mm/s, post-test speed of 10 mm/s, and a trigger force of 0.05 N. Hardness (N) was defined as the maximum force required to fracture the sample, and crispiness was indicated by the number of force peaks during the fracture event. Fifteen replicates per drying condition were analyzed.

Water Activity Measurement

The water activity of the dried samples was measured at 25 ℃ using a calibrated water activity meter (Novasina, Model LabMaster-aw, Switzerland). Approximately 5 g of ground sample was placed in the instrument's sample cup, and the measurement was initiated. Readings were recorded once equilibrium was achieved (after 20-30 minutes). Triplicate measurements were taken for each batch.

Statistical Analysis

All quality attribute data (color, texture, water activity) were subjected to one-way Analysis of Variance (ANOVA) using SPSS software (Version 13, SPSS Inc., Chicago, IL). The significance of differences between mean values was determined using Duncan's Multiple Range Test at a 95% confidence level ($p < 0.05$).

Results and Discussion

Drying Kinetics of Salmon Skin

The drying kinetics of salmon skin subjected to a multi-stage combined process, initial HA drying at 90℃, followed by MW puffing, and concluding with HA finishing are illustrated in Fig.s 2 and 3. The data indicate that both MW power and puffing duration are critical factors influencing total drying time, primarily by enhancing the internal moisture removal rate through volumetric heating.

As shown in Fig. 2, increasing the MW power during the puffing stage significantly affects the overall drying kinetics. With a constant puffing time of 1 minute, elevating the MW power from 450 W to 600 W, and then to 800 W, resulted in a marked and non-linear reduction in total drying time. Specifically, the time needed to achieve the target final moisture content decreased from 231 minutes at 450 W to 141 minutes at 600 W, and was further reduced to just 51 minutes at 800 W. This represents a total reduction of approximately 78% when increasing the power from the lowest to the highest setting.

This dramatic acceleration is a direct result of the fundamental mechanism of MW heating, where electromagnetic energy is converted into heat volumetrically within the

material [16, 17]. Higher MW power levels induce more rapid and intense internal heating, generating greater steam pressure. This pressure serves as a powerful driving force for moisture, facilitating its quick expulsion from the interior to the surface. Consequently, the material enters the final HA drying stage with a significantly lower moisture content, thereby shortening the overall process. These findings align with those reported by Nathakaranakule et al. [18], who investigated step-down MW power drying of durian chips and found that increasing MW power from 600 W to 800 W significantly reduced the total drying time, attributing this acceleration to enhanced internal steam generation. Similarly, Verma et al. [19], studied MW drying of kadal shrimp and discovered that higher MW power levels significantly reduced drying time due to increased temperature gradient and vapor pressure within the shrimp tissue.

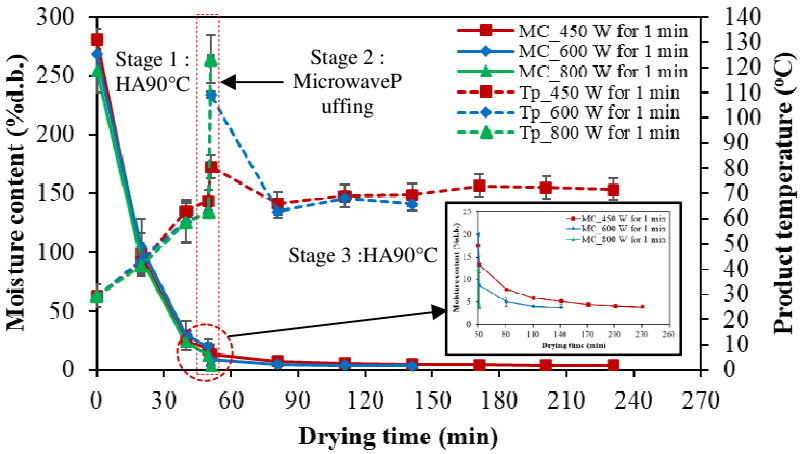


Figure 2 Change in moisture content of salmon skin at MW puffing powers of 450, 600 and 800 W for 1 min at an intermediate moisture content of 10% (d.b.).

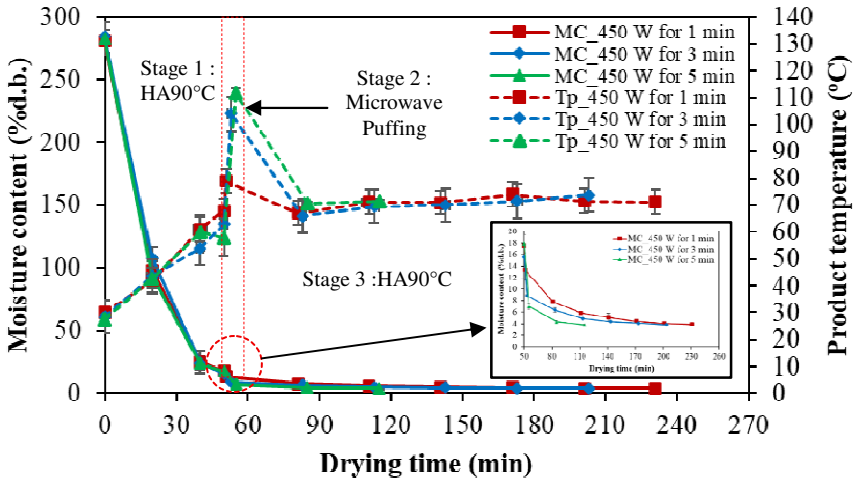


Figure 3 Change in moisture content of salmon skin at a MW puffing power of 450 W for 1, 3 and 5 min at an intermediate moisture content of 10% (d.b.).

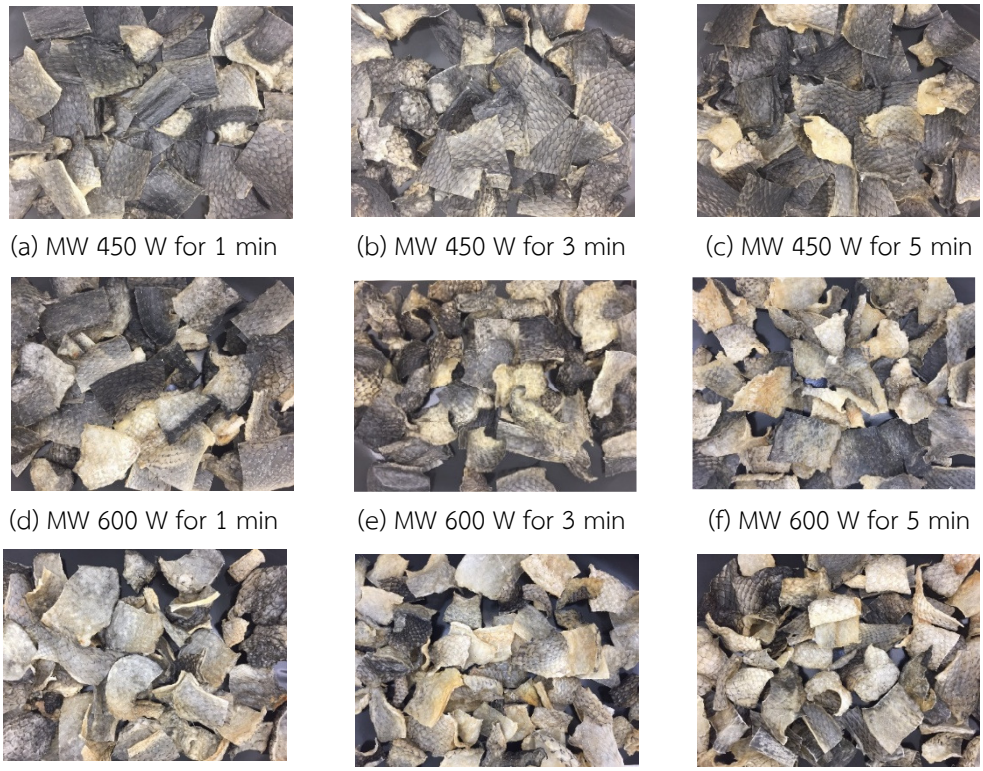
The duration of the MW puffing stage, at a fixed power of 450 W, also significantly influenced the drying kinetics, as depicted in Figure 3. Extending the puffing time from 1 to 3 minutes reduced the total drying time by 30 minutes, while a further increase in puffing time to 5 minutes resulted in an additional reduction of 90 minutes compared to the 3 minutes treatment. Thus, the total time saved by increasing the puffing duration from 1 to 5 minutes at 450 W was 120 minutes.This phenomenon can be explained by two synergistic effects of prolonged MW exposure. First, a longer duration allows more internal moisture to be converted into vapor and removed directly during the puffing stage itself.[20] Second, and perhaps more importantly, this sustained vapor generation creates a more porous internal structure by forming extensive vapor channels. These results align with the findings of Raikham et al. [21], who studied fluidized bed puffing for producing crispy banana snacks. They reported that the relationship between puffing time and intermediate moisture content is non-linear. The authors emphasized that controlling the intermediate moisture content is crucial for maximizing puffing efficiency and reducing shrinkage during post-processing. Furthermore, Teeta et al. [10], investigated the effect of MW power and puffing time on the quality of yam bean crackers and found that increasing puffing time from 30 to 60 seconds at MW power of 800 W significantly reduced the moisture content. The higher degree of puffing induced the higher heat transfer rate, which rapidly increased the sample temperature, creating a more porous structure leading to even larger volume expansion and crispier textures [22].

Color of dried salmon skin

Table 1 Color parameters of dried salmon skin produced under different puffing conditions using a multi-stage drying method.

Drying methods	Puffing time (min)	*L**	*a**	*b**	Drying time (min)
HA90°C/MW450W/ HA90°C	1	47.48±1.35^{f}	-0.17±0.14^{a}	0.25±0.15^{a}	231
	3	45.12±1.73^{e}	0.25±0.25^{b}	0.54±0.17^{a}	203
	5	43.83±1.39^{de}	0.27±0.10^{b}	0.65±0.18^{a}	145
HA90°C/MW600W /HA90°C	1	42.63±1.25^{d}	0.33±0.39^{b}	2.12±0.78^{b}	141
	3	40.82±0.56^{c}	0.40±0.19^{b}	2.83±0.81^{b}	113
	5	37.90±1.52^{b}	0.42±0.22^{b}	4.86±1.01^{c}	85
HA90°C/MW800W/ HA90°C	1	37.83±1.28^{b}	0.53±0.24^{b}	6.71±0.55^{d}	55
	3	35.80±1.49^{a}	1.50±0.35^{c}	7.90±1.19^{e}	53
	5	35.51±1.77^{a}	1.59±0.35^{c}	9.17±0.77^{f}	51

Different superscript letters in the same column indicate significant differences at $p < 0.05$., [HA drying/MW Puffing/HA drying, / is followed by].



(a) MW 450 W for 1 min (b) MW 450 W for 3 min (c) MW 450 W for 5 min

(d) MW 600 W for 1 min (e) MW 600 W for 3 min (f) MW 600 W for 5 min

(g) MW 800 W for 1 min (h) MW 800 W for 3 min (i) MW 800 W for 5 min

Figure 4 Color of dried salmon skin at different puffing conditions.

The color parameters of dried salmon skin, processed using a multi-stage technique, are summarized in Table 1, with the final products shown in Figure 4. Statistical analysis revealed that both MW power and puffing time significantly influenced all color coordinates. Color is crucial for consumer acceptance of snack products, as it impacts purchasing decisions.

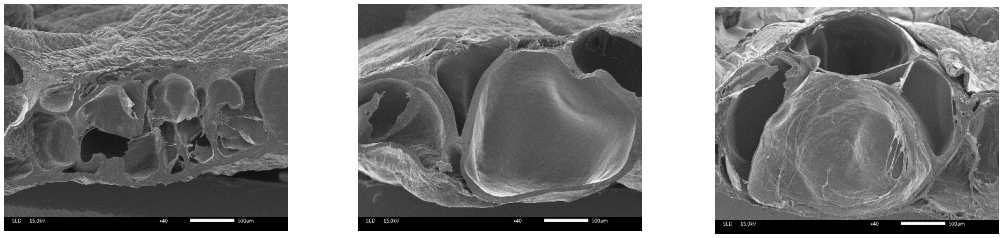
Lightness values (L*) ranged from 35.51 to 47.48, with an inverse relationship observed between processing intensity and lightness. Increasing MW power from 450 W to 800 W at a constant 1 minute puffing time decreased lightness from 47.48 to 37.83. Extending puffing time at 800 W further reduced the L* value to 35.51. This darkening is visually represented in Fig. 4, where samples processed at 450 W appear light-colored (Fig. 4a), while those at 800 W for 5 minutes show a distinct golden-brown color (Fig. 4i). The darkening results from non-enzymatic browning reactions, particularly the Maillard reaction and caramelization [23]. The rapid internal heating during MW processing accelerates these reactions. Similar findings by Paengkanya et al. [24] on mango slice and Huang et al. [25] on green peppers support this observation.

Chromaticity coordinates *a** (red-green) and *b** (yellow-blue) also significantly increased with more intense drying parameters. The *a** values rose from -0.17 at 450 W to 1.59 at 800 W, while *b** values increased from 0.25 to 9.17. This change reflects the formation of melanoidins and other pigments during the Maillard reaction [26-27]. At 5 minutes of puffing time, the product dried at 800 W had significantly higher *a** and *b** values than that dried at 600 W. This emphasizes that higher MW power drives pigment formation, as supported by Verma et al. [19] in their study of brown shrimp.

Comparisons with other snack products reveal both similarities and material-specific responses. Kantrong et al. [28] studied puffing technique on physical and functional properties of purple sweet potatoes snack and found that increasing MW power from 210 W to 560 W tend to decreased *L** values, consistent with current findings. The pronounced color change in salmon skin, likely due to its higher protein content facilitating Maillard reactions. Aykın-Dinçer et al. [29] reported that dried beef chips at higher MW power exhibited darker colors with increased redness and yellowness, seen as desirable for consumer acceptance. While intense browning can be undesirable for certain foods, the golden-brown color of salmon skin snacks processed at 800 W is associated with the appealing appearance of dried tilapia skin snacks [30]. The color parameters of these processed samples, the *L**, *a**, and *b** fell within the ranges of 35-37, 1.5-1.6, and 7-9, respectively. The MW power and puffing time significantly influence the color of dried salmon skin; more intense processing results in products that are darker, redder, and yellower due to enhanced Maillard reactions. These findings are consistent with existing literature on MW processing of protein-rich foods, which produces visually appealing snacks, particularly at 800 W.

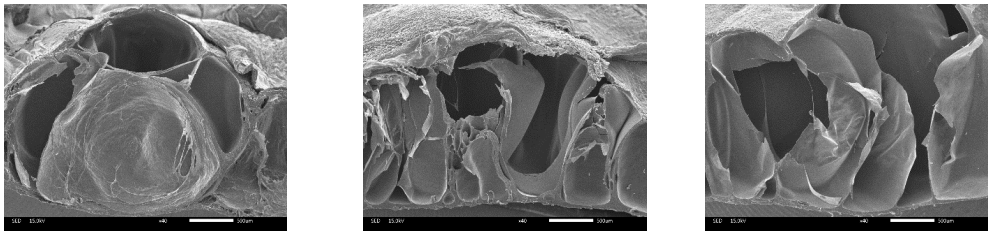
Microstructure of Dried Salmon Skin

The microstructural evolution of salmon skin, as revealed by cross-sectional scanning electron microscopy, provides key insights into the physical transformations induced by the multi-stage drying technique. Fig. 5 and 6 illustrate how MW power and puffing time significantly affect the pore structure of the final product, closely linked to drying kinetics discussed in Section 3.1 and the textural properties in Section 3.4. At a constant puffing time of 1 minute, samples treated at 450 W (Fig. 5a) showed a dense matrix with minimal pores, leading to a longer drying time of 231 minutes due to limited moisture diffusion. In contrast, at 600 W (Fig. 5b), the number and size of pores increased, enhancing moisture movement, while 800 W treatments (Fig. 5c) resulted in a spongy, expanded matrix with large pores, drastically reducing drying time to 55 minutes.



(a) Puffing at MW 450 W (b) Puffing at MW 600 W (c) Puffing at MW 800 W

Figure 5 Microstructural cross-section of dried salmon skin from multi-stage drying with MW puffing at 450-800 W for 1 min



(a) Puffing for 1 min (b) Puffing for 3 min (c) Puffing for 5 min

Figure 6 Microstructural cross-section of dried salmon skin from multi-stage drying with MW puffing at 450 W for -15 min.

This rapid transformation is driven by the volumetric heating of MW energy, which converts internal moisture into steam, increasing vapor pressure and expanding the protein and collagen matrix [24]. Increasing puffing duration at a fixed power of 450 W also affected

structure, as shown in Fig. 6. A 1 minute puff (Fig. 6a) led to minor expansion, while 3 minutes (Fig. 6b) yielded medium-sized pores, and 5 minutes (Fig. 6c) produced larger voids, albeit less uniform than those from high-power, short treatments. This progressive change is due to increased internal temperature and vapor pressure over time [31]. The observed microstructural changes align with drying kinetics data from Section 3.1, with drying time decreasing from 231 minutes at 1 minute of puffing to 145 minutes at 5 minutes, due to the formation of vapor channels. Comparisons with other protein-based snacks, such as those studied by Simão et al. [32] showed that while increased MW power initially promotes pore formation, excessive exposure can lead to structural collapse. In this study, no collapse was observed, suggesting that salmon skin may be more structurally resilient under these conditions.

Texture and water activityof dried salmon skin

The textural properties and water activity of dried salmon skin play a vital role in determining product quality and shelf stability, which are affected by various drying parameters, as summarized in Table 2. Texture is particularly important for consumer acceptance of puffed snacks; ideally, these snacks should have low hardness (making them easy to bite) and high crispiness (providing a satisfying crunch).

Table2 Texture and water activity of dried salmon skin at various drying conditions

Drying methods	Puffing time (min)	Hardness (N)	Number of peaks	Water activity	Drying time (min)
HA90°C/MW450W/ HA90°C	1	2.70±26.11^{e}	4.5±02.17^{a}	0.380.004±4^{b}	231
	3	23.842.57±^{de}	±5.33225.^{ab}	0.390.003±7^{c}	203
	5	2.72±21.86^{d}	1.26±6.00^{abc}	0.004±0.361^{a}	145
HA90°C/MW600W/ HA90°C	1	18.59±2.85^{c}	2.41±7.86^{bcd}	0.40.010±77^{f}	141
	3	2.84±16.69^{bc}	2.89±8.50^{cd}	00.007±411.^{d}	113
	5	±16.31219.^{bc}	92.54±14.^{d}	0.500.006±0^{g}	85
HA90°C/MW800W /HA90°C	1	12.63±4.33^{ab}	2.59±12.50^{e}	00.008±388.^{bc}	55
	3	2.16±13.94^{ab}	2.71±20.89^{f}	00.010±397.^{c}	53
	5	2.91±13.02^{a}	2.91±21.60^{f}	0.450.007±3^{e}	51

Different superscript letters in the same column indicate significant differences at $p < 0.05$., [HA drying/MW Puffing/HA drying, / is followed by].

Hardness, defined as the maximum force required to fracture a sample, varied significantly ($p<0.05$), ranging from 13.02 N to 26.11 N. The number of force peaks, which serves as an objective indicator of crispiness, ranged from 4.50 to 21.60; a higher number of peaks indicates a crispier texture with multiple small fractures. A strong inverse correlation was observed between hardness, peak count, and MW power. Increasing the puffing power from 450 W to 800 W for one minute resulted in a 38-76% reduction in hardness and a highest peak count of 21.6, which nearly increased fivefold. Higher power levels lead to greater internal vapor pressure, creating a more porous matrix that fractures easily [22]. Similar findings were reported by Paengkanya et al. [7] in their study of durian chips, where increased MW power reduced hardness and improved crispiness. The present study demonstrates a

more significant improvement in texture due to higher power levels and the unique properties of salmon skin, which is more responsive to MW puffing.

Crispiness did not decline in this study; at 800 W, the peak count increased from 12.50 at 1 minute to 21.60 at 5 minutes. This suggests that maximum microstructure expansion occurs by 3 minutes at 800 W, with additional energy input not significantly affecting texture. The high collagen content in salmon skin may explain its resilience under these conditions.

The effect of puffing time on texture was more complex than that of power levels. Increasing puffing time from 1 to 5 minutes at a given power level generally resulted in decreased hardness and increased peak count. For example, at 450 W, hardness dropped from 26.11 N to 21.86 N while the peak count rose from 4.50 to 6.00. This trend indicates progressive pore development, as illustrated in Fig. 6. At 600 W, hardness decreased from 18.59 N to 16.31 N, with peak count increasing from 7.86 to 9.14. However, at 800 W, no significant differences in texture were observed between 3 and 5 minutes, indicating a plateau in microstructure expansion.

All samples demonstrated water activity values ranging from 0.361 to 0.500, which is below the safety threshold of 0.6. This level effectively inhibits the growth of spoilage microorganisms. At water activity levels below 0.6, most pathogenic bacteria, including *Salmonella spp*., *Staphylococcus aureus*, and *Clostridium botulinum*, cannot thrive [33]. Based on the observed water activity range, the expected shelf life of the snacks at ambient temperature is 3 months approximately when packaged under vacuum conditions [34].

Specific energy consumption of the drying process

The SEC is a crucial parameter for evaluating the industrial feasibility of a drying process. This analysis focused on the multi-stage combined drying of salmon skin, examining the effects of varying MW power levels and puffing durations. The results are summarized in Table 3. The findings indicate that integrating MW puffing significantly enhances energy efficiency, especially at higher power levels and longer puffing times. One notable trend is the substantial reduction in total SEC achieved by increasing MW power. For example, when maintaining a constant puffing time of 1 minute, raising the MW power from 450 W to 800 W led to a sharp decline in SEC_{total} from 929.35 MJ/kgH_2O to 595.86 MJ/kgH_2O. This represents an improvement in energy efficiency of approximately 36%. This enhancement is primarily due to the significant reduction in total drying time, which decreased from 231 minutes to 55 minutes, as detailed in Section 3.1. The rapid volumetric heating generated by MW energy facilitates immediate moisture evaporation, thereby reducing reliance on prolonged HA drying that depends on slower conductive and convective heat transfer mechanisms [29-30]. Consequently, although the input of MW energy increases, it is offset by substantial savings in thermal energy consumption during the subsequent drying stages.

Table 3 Specific Energy Consumption of drying processes under various conditions.

Drying methods	Puffing time (min)	Specific energy consumption (MJ/kgH_2O)					
		Before puffing		Puffing	After puffing		Total Energy
		Heater	Blower	Microwave	Heater	Blower	
HA90°C/MW450W/ HA90°C	1	194.46±2.55^{a}	4.16±0.81^{a}	0.45±0.00^{a}	676.18±1.56^{h}	15.15±2.81^{g}	929.35±2.86^{g}
	3	193.35±1.20^{a}	4.08±0.79^{a}	1.31±0.01^{d}	559.34±3.85^{g}	12.83±0.72^{g}	914.66±1.51^{f}
	5	193.18±2.10^{a}	4.08±0.87^{a}	2.18±0.02^{f}	363.95±3.54^{f}	10.48±0.94^{f}	799.23±2.49^{e}
HA90°C/MW600W/ HA90°C	1	190.60±2.33^{a}	4.08±0.86^{a}	0.58±0.01^{b}	361.70±3.23^{f}	9.32±1.92e^{f}	800.88±2.11^{e}
	3	192.68±2.15^{a}	4.99±0.46^{a}	1.76±0.02^{e}	355.15±3.61^{e}	7.04±0.89^{e}	607.98±3.19^{d}
	5	193.76±1.18^{a}	5.01±0.38^{a}	2.95±0.02^{h}	137.73±2.38^{d}	4.72±0.80^{d}	593.29±1.32^{c}
HA90°C/MW800W/ HA90°C	1	193.90±2.60^{a}	4.07±0.79^{a}	0.78±0.01^{c}	38.15±1.20^{c}	1.02±0.12^{c}	595.86±3.68^{c}
	3	192.92±2.95^{a}	4.93±0.46^{a}	2.32±0.03^{g}	25.84±0.95^{b}	0.88±0.08^{b}	581.43±2.54^{ab}
	5	192.62±1.50^{a}	4.92±0.36^{a}	3.86±0.04^{i}	18.42±0.75^{a}	0.61±0.05^{a}	577.10±2.25^{a}

Different superscript letters in the same column indicate significant differences at $p < 0.05$. [HA drying/ MW Puffing/ HA drying, / is followed by].

Furthermore, extending the puffing duration at a given MW power further optimizes energy use. At 450 W, increasing the puffing time from 1 minute to 5 minutes reduced the SEC_{total} from 929.35 to 799.23 MJ/kgH_2O, an overall reduction of 14%. This reduction can be attributed to the enhanced microstructural expansion induced by longer MW exposure, which creates a more porous matrix. This structural change decreases moisture diffusion resistance during the final HA stage, shortening its duration and reducing energy demand. At 800 W, the final HA drying stage was significantly shortened due to the efficient moisture removal during MW puffing. This resulted in the lowest SEC_{total} values observed across all tested conditions. Specifically, at 800 W with 5 minutes of puffing, the SEC_{total} reached 577.10 MJ/kgH_2O, which is considerably lower than all other conditions tested. This finding aligns with the principles outlined by Paengkanya et al. [24] and Nathakaranakule et al. [18] confirming that MW-assisted drying can significantly enhance energy efficiency by minimizing extended convective drying phases.

The use of high-power MW puffing, particularly at 800 W, not only improves product quality evidenced by better texture, color, and microstructure but also represents the most energy-efficient approach for producing ready-to-eat salmon skin snacks. This balance between quality and efficiency highlights the potential of MW-assisted multi-stage.

Conclusions

This study demonstrated that a multi-stage drying method combining hot-air drying and MW puffing can transform underutilized salmon skin into a ready-to-eat puffed snack. Key parameters of MW puffing, particularly power level and duration, significantly impacted drying kinetics, product quality, and energy efficiency. Increasing MW power from 450 W to 800 W and puffing time from 1 to 5 minutes reduced drying time by up to 78%, which facilitated

rapid moisture removal. Scanning electron microscopy revealed that higher power and longer puffing created more porous microstructures, improving textural quality. Hardness decreased by 76%, and crispiness nearly increased fivefold. Intense MW power also promoted non-enzymatic browning, resulting in darker products with increased redness and yellowness color. All samples-maintained water activity below 0.5, ensuring microbiological safety. Energy efficiency improved significantly, with the drying conditions of initial hot-air drying at 90 °C, followed by MW puffing at 800 W for 5 minutes and final hot-air drying at 90 °C which wasreducedthe total SEC reached to 577.10 MJ/kgH_2O.

Acknowledgments

The research team thanks Rajamangala University of Technology Phra Nakhon for its support of the 2020 research budget (contract number 63-1306-01/3). We also appreciate the Research Laboratory for Drying Food and Advanced Biological Materials at King Mongkut's University of Technology Thonburi and the Faculty of Agriculture at Rajamangala University of Technology Srivijaya, Nakhon Si Thammarat Campus, for providing essential research equipment.

References

[1] Food and Agriculture Organization of the United Nation. (2022). *Globefish Quarterly Salmon Analysis*. Available from https://openknowledge.fao.org/items/a7b7eedb-568c-4b13-ba22-3c987925ee0d. Accessed date: 20 February 2026.

[2] Ramakrishnan, V. V., et al. (2024). Salmon Processing Discards: A Potential Source of Bioactive Peptides – A Review. *Food Production, Processing and Nutrition*, *6*(1), 22.

[3] Dangal, A., et al. (2024). Review on Deep-Fat Fried Foods: Physical and Chemical Attributes, and Consequences of High Consumption. *European Food Research and Technology*, *250*(6), 1537–1550.

[4] Aboud, S. A., et al. (2019). A Comprehensive Review on Infrared Heating Applications in Food Processing. *Molecules*, *24*(22), 4125.

[5] Somjid, S., et al. (2026). Comparative Study of Drying Techniques on the Functional Properties and Fishy Odor Characteristics of Gelatin Derived From Atlantic Salmon (*Salmo salar*) Skin. *Biocatalysis and Agricultural Biotechnology*, *76*, 104218.

[6] Ruan, J., et al. (2025). Optimization of the Vacuum Microwave Drying of Tilapia Fillets Using Response Surface Analysis. *Foods*, *14*, 873.

[7] Paengkanya, S., et al. (2015). Application of Microwave for Drying of Durian Chip. *Food and Bioproducts Processing*, *96*, 1–11.

[8] Liang, X., et al. (2023). Effect of Microwave Drying on the Brittleness Quality of Pork

Chip Snacks: Perspectives on Drying Kinetics and Microstructural Traits. *LWT*, *185*, 115147.

[9] Sompong, R., & Songsermpong, S. (2022). Production Method and Optimization of Puffing Tofu Skin Snack Using Home Microwave Oven. *Agriculture and Natural Resources*, *56*(3), 525–536.

[10] Teeta, S., et al. (2024). Effect of Microwave Power and Puffing Time on the Quality of Yam Bean Cracker. *Nanotechnology Perceptions*, *20*(S6), 1061–1073.

[11] Nguyen, T. T., et al. (2013). Shrimp Cassava Cracker Puffed by Microwave Technique: Effect of Moisture and Oil Content on Some Physical Characteristics. *Kasetsart Journal - Natural Science*, *47*(3), 434–446.

[12] Chedoloh, R., & Waeno, M. (2020). The Effect of Industrial Microwave Power Level on Physical and Chemical Properties of Semi-Finished Fish Crackers. *The Journal of Applied Science*, *19*(2), 129–144.

[13] AOAC. (1995). *Official Methods of Analysis* (16th ed.). Association of Official Analytical Chemists.

[14] Balaras, C. A., et al. (2023). Primary Energy Factors for Electricity Production in Europe. *Energies*, *16*, 93.

[15] Wilby, M. R., et al. (2014). Empirical and Dynamic Primary Energy Factors. *Energy*, *73*, 771–779.

[16] Gong, S., et al. (2025). Microwave Drying of *Tricholoma matsutake*: Dielectric Properties, Mechanism, and Process Optimization. *Foods*, *14*(17), 3054.

[17] Rattanadecho, P., & Makul, N. (2016). Microwave-Assisted Drying: A Review of the State -of-the-Art. *Drying Technology*, *34*(1), 1–38.

[18] Nathakaranakule, A., et al. (2019). Durian Chips Drying Using Combined Microwave Techniques With Step-Down Microwave Power Input. *Food and Bioproducts Processing*, *116*, 105–117.

[19] Verma, S. K., et al. (2024). Effects of Different Microwave Power on the Drying Kinetics and Physicochemical Quality of Brown Shrimp (*Metapenaeus dobsoni*). *Sustainable Food Technology*, *2*(1), 141–151.

[20] Man, Y., et al. (2022). Study on Intermittent Microwave Convective Drying Characteristics and Flow Field of Porous Media Food. *Energies*, *16*(1), 441.

[21] Raikham, C., et al. (2013). Optimum Conditions of Fluidized Bed Puffing for Producing Crispy Banana. *Drying Technology*, *31*(6), 726–739.

[22] Tabtiang, S., et al. (2023). Effects of Thermal Pretreatment and Puffing Medium Variously Modify the Microstructure and Quality of Crisps Obtained From Two Banana Varieties. *Journal of Stored Products Research*, *104*, 102199.

[23] Bal, L. M., et al. (2011). Kinetics of Colour Change of Bamboo Shoot Slices During Microwave Drying. *International Journal of Food Science & Technology*, *46*(4), 827–

833.

[24] Paengkanya, S., et al. (2025). Drying Ripe Mango Slices Using Step-Down Temperature Far-Infrared-Hot Air Techniques. *International Journal of Agricultural and Biological Engineering*, *18*(6), 281–289.

[25] Huang, Y., et al. (2025). Metabolomics Analysis Reveals the Non-Enzymatic Browning Mechanism of Green Peppers (*Piper nigrum* L.) During the Hot-Air Drying Process. *Food Chemistry*, *464*, 141654.

[26] Ding, W., et al. (2025). Influence of Nonenzymatic Browning Reactions on the Digestibility and Gut Microbiota Fermentation of Starch and Protein. *Comprehensive Reviews in Food Science and Food Safety*, *24*(6), e70299.

[27] Qi, Y., et al. (2025). Maillard Reaction in Flour Product Processing: Mechanism, Impact on Quality, and Mitigation Strategies of Harmful Products. *Foods*, *14*(15), 2721.

[28] Kantrong, H., et al. (2022). Effects of Extrusion Temperature and Puffing Technique on Physical and Functional Properties of Purpled Third-Generation Snack After Heat Treatment. *Journal of Food Science and Technology*, *59*(6), 2209–2219.

[29] Aykın-Dinçer, E., et al. (2021). Drying Kinetics and Quality Characteristics of Microwave -Assisted Hot Air Dried Beef Chips. *Journal of Microwave Power and Electromagnetic Energy*, *55*(3), 219–235.

[30] Wang, L., et al. (2022). Physicochemical and Sensory Properties of a Tilapia Skin-Based Ready-to-Eat Snack Prepared by Infrared Drying and Air Frying. *Applied Food Research*, *2*, 100155.

[31] Duan, L., et al. (2018). Evolution of Pore Structure During Microwave Freeze-Drying of Chinese Yam. *International Journal of Agricultural and Biological Engineering*, *11*(6), 208–212.

[32] Simão, R. S., et al. (2025). Mozzarella Cheese Snacks Produced by Microwave Vacuum Drying: Protein Profile, Protein Digestibility, Flavor, and Texture. *Food Chemistry*, *478*, 143660.

[33] Syamaladevi, R. M., et al. (2016). Influence of Water Activity on Thermal Resistance of Microorganisms in Low-Moisture Foods: A Review. *Comprehensive Reviews in Food Science and Food Safety*, *15*(2), 353–370.

[34] Carter, B. P., et al. (2017). A Hygrothermal Model for Predicting Shelf Life in Infant Formula. In *The 8th Shelf Life International Meeting* (p.33-38). 1–3 November, 2017, Bangkok, Thailand.