Microwave Vacuum Puffing Technology for Food Products: a Review

Zhi Chang[1, a], Tong Liu[1, b], Ke Wang[1, c], Chao Mao[1, d *]

[1] College of Food Science and Engineering, Northwest A&F University, Yangling 712100, China.

[a] chang677@outlook.com, [b] 17629887936@163.com, [c] wangkejxsj@nwafu.edu.cn,

[d] maochao@163.com

[a, b] Zhi Chang and Tong Liu are co-first authors of the article.

Abstract. Puffed food is popular because of its loose structure, crisp taste, and broad market prospects. The traditional frying puffing method has been gradually abandoned due to health problems such as cardiovascular disease, hypertension, etc., and replaced by low-temperature and healthy processing methods. As a new puffing technology, microwave vacuum puffing (MVP) combines the instantaneousness of microwave heating and the low temperature of vacuum drying, which can better retain the color, aroma, taste, and nutritional components of food. This paper introduces the principle and processing characteristics of MVP. The process parameters, product quality, puffing kinetics, mass transfer, heat transfer kinetics, and processing equipment were reviewed. Finally, the future development and trend of this technology were discussed.

Keywords: Microwave vacuum puffing, processing parameters, puffing kinetics, heat and mass transfer.

1. Introduction

Puffed snacks are popular due to their crispy, delicious, and convenient nature [1]. Traditional deep-fried puffed foods pose health risks due to high oil content, harmful substances like acrylamide, and rapid starch digestion, leading to issues like cardiovascular disease, hypertension, diabetes, cancer, and obesity [2].

MVP combines microwave heating and vacuum's low temperature, enabling rapid, uniform, energy-efficient dehydration and puffing [3]. MVP retains original food color, aroma, taste, vitamins, and reduces loss of heat-sensitive nutrients and active components. Moreover, the materials treated with MVP have better puffing effects in terms of increasing volume and crispy taste [4]. Because of the excellent processing characteristics of MVP, it has attracted the attention of the food industry and research scholars (Fig. 1). At present, this technology has been widely applied to the processing of food products.

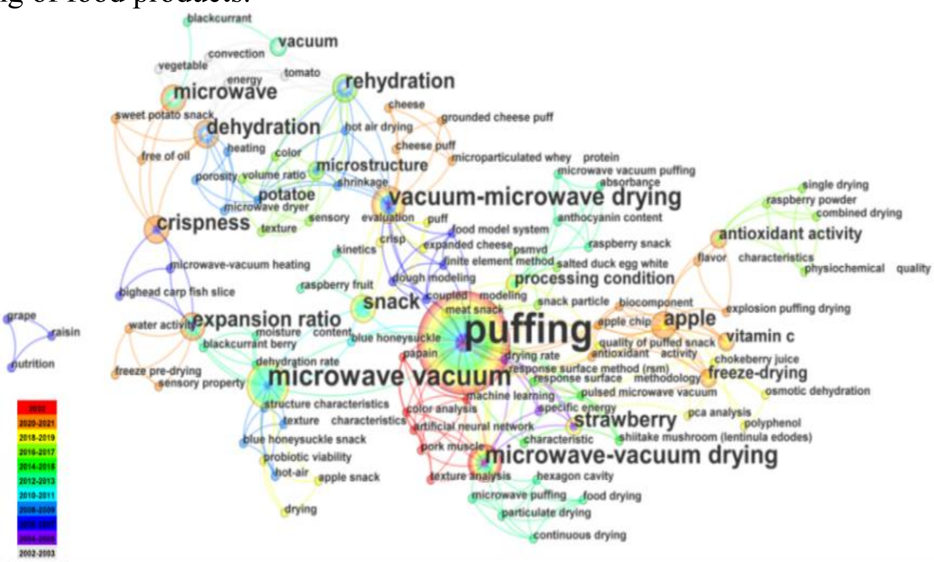

Fig. 1 Visualization of the research trend of MVP in the past two decades

2. Overview of Microwave Vacuum Puffing Technology

2.1 Mechanism of MVP

MVP uses microwave energy to heat food materials, causing volume expansion under vacuum conditions. Microwave heating is a type of dielectric heating. Microwave radiation causes polar ions or molecules in food to rotate, generating heat and causing water evaporation [5]. Steam generation and accumulation create a strong radial force to remove steam. The temperature and pressure differences enhance steam discharge, creating a 'pumping effect' [6]. When internal vapor pressure exceeds the cell's structural tension, it expands, forming a loose, uniform porous or honeycomb structure. In order to obtain a better puffing effect, hot air drying is generally used as a pretreatment to dry the material’s surface to form a gas-blocking surface layer [7]. As the boiling point of water decreases with increasing vacuum, vacuum-assisted microwave heating can puff materials at lower temperatures, retaining more nutrients and flavor. Additionally, vacuum pump kinetic energy accelerates surface moisture separation, enabling rapid drying [8]. MVP combines rapid microwave heating with low-temperature vacuum drying, offering fast heating, efficient drying, and low-temperature expansion.

2.2 MVP System Composition

Fig. 2 shows a picture of vacuum microwave equipment of semi-industrial scale with magnetrons and a vacuum pump. Microwave radiation is generated by a magnetron that converts electrical energy into electromagnetic energy. The sample was placed in two round trays, and the rotation speed and the output power were set. The microwave was applied under a temperature-controlled system and automatically regulated the control of introduced microwaves (on-off cycles) depending on the temperature. The vacuum chamber pressure was reduced to a defined absolute pressure, and the end of the process was determined by a preliminary approach attempting to reach a constant mass. All the parameters were determined by preliminary studies.

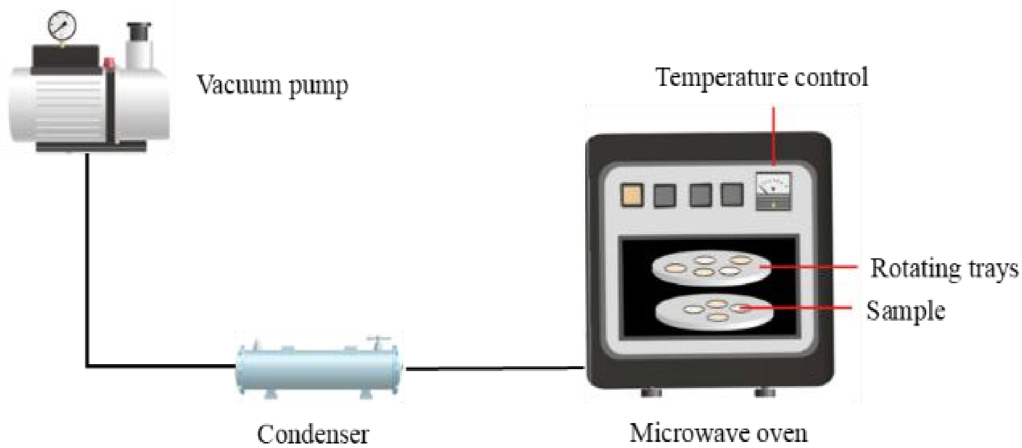

Fig. 2 Schematic representation of microwave vacuum puffing system [5]

3. The Research Status

3.1 Influential Factors

MVP is controlled by several system parameters, including microwave power (W), vacuum (kPa) frequency (Hz), puffing temperature (°C), initial moisture content (%), puffing time (s), food composition and dielectric properties, etc. These parameters are interconnected and need to be optimized according to the specific food material [9].

3.1.1 Initial moisture content

The MVP process involves dehydration and volume expansion. The moisture on the food's surface absorbs microwave energy and evaporates quickly at low temperatures. This process may cause the food's surface to harden and prevent further evaporation of internal moisture. When moisture content drops to a critical value, residual moisture inside the food absorbs microwave energy but struggles to diffuse out, increasing internal pressure. This phenomenon (called puffing) will cause the volume of food to expand and create a porous structure. Pawlak et al. [10] stated that pre-drying to a critical moisture value and forming a dry surface layer is necessary for MVP. The expansion level of MVP depends on steam generation and the material's mechanical properties. Vapor generation is influenced by microwave intensity, while the mechanical properties are determined by the moisture content of the materials [4]. When the moisture content is too low, the gradient pressure formed by water evaporation is not enough to destroy the structure of the structural fiber, and the purpose of expansion cannot be achieved. If moisture content is too high, not all water vaporizes. The remaining liquid water's surface tension bonds cells, hindering expansion [11]. Therefore, the optimum initial moisture content should be determined before MVP. Table 1 shows that plant-based food initial moisture content is generally below 40%, while animal-based food is below 72%. This may be due to the fact that a smaller vapor pressure can break animal cell tension and cause expansion.

3.1.2 Microwave intensity

Waves in the 915 MHz-3 GHz range are easily absorbed by water, fat, and sugar in food. The common frequency for food is 2.45 GHz [12]. In the MVP process, microwave energy is absorbed by water molecules, causing fluctuating movement. Higher microwave power accelerates this movement and shortens expansion time. Liu et al. [13] mentioned that microwave power negatively correlates with expansion time but positively with expansion rate. Microwave power accelerates puffing by causing berry leathers to absorb energy, generating volumetric heating and instant moisture evaporation, leading to expansion. However, excessive microwave power can accelerate surface water evaporation, weakening viscoelasticity and hindering expansion [14]. Liu et al. [15] further found in mushroom puffing experiments that microwave power correlates positively with expansion rate at low moisture, but has little effect when moisture exceeds 30%. When the moisture content was more than 35%, only surface water was removed, and the inflation of the sample remained stable. Thus, the volume expansion ratio under MVP conditions depends on microwave intensity, vacuum pressure, moisture content, material mass, and viscoelastic modulus [14].

3.1.3 Vacuum degree

During MVP process, vacuum pressure accelerates water movement from the inside to the surface, creating a porous structure. Wang et al. [16] and Liu et al. [17] postulated that vacuum pressures between 30 and 90 kPa enhance food expansion. Zheng et al. [4] studied vacuum pressures (55, 75, 85 kPa) on berry slab expansion. At 35 g/100 g moisture and 2.68 kW microwave power, 75 kPa achieved the highest expansion ratio. Both too-high and too-low vacuum pressure led to a low expansion rate. This was because low vacuum pressure provides insufficient driving force for expansion. Excessive pressure raises the temperature quickly, enhancing surface evaporation and forming a solid layer that hinders expansion [13]. Moreover, the too-low vacuum can cause breakdown discharge, affecting microwave equipment use by reducing the breakdown field strength of water vapor and air [18]. Therefore, it is not necessary to select the maximum vacuum degree during MVP. An optimal vacuum degree in MVP can reduce energy consumption and enhance expansion.

3.1.4 Dielectric properties

The dielectric properties (DPs, ε^*) of food refer to the response characteristics of the bound charge inside the food to the applied electric field. The main parameters to evaluate the dielectric properties including dielectric constant(ε') and dielectric loss factor(ε''), as shown in Equation 1.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

where $j = \sqrt{-1}$

The dielectric constant represents the ability of the material to store the electric field energy, and the reaction dielectric material improves its ability to accommodate microwave electromagnetic energy. While the loss factor reflects the energy loss of the dielectric in the electric field, and it is mainly manifested in the ability to convert microwave energy into heat energy during MVP [19].

The power penetration depth (dp) is defined as the distance at which the power density drops to a value of 1/e (e=2.718) from its value at the surface and is expressed as:

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+(\varepsilon''/\varepsilon')^2}-1\right]}} \quad (2)$$

where c is the speed of light in free space (3 × 108 m/s) and f is the frequency (Hz) [20]. Therefore, the penetration depth of microwaves can be calculated according to the dielectric properties. The penetration depth is used to predict the thickness of the materials to be heated during the heating process to ensure heating efficiency and temperature uniformity during the heating process [21].

The heat absorbed per unit volume of food can be calculated by Equation 3:

$$Q = 55.6 \times 10^{-12} f e'' E^2 \quad (3)$$

where f is the frequency (Hz), and E2 is the electric field strength (V/m). As equation 2 and 3 stated, the higher dielectric loss factor involved more significant heat generated in the food matrix but resulted in less penetration depth and greater surface heating [22]. Food with high moisture content and dielectric loss coefficient in contact with microwave radiation could increase the dipole rotation of water molecules, promoting the conversion of electromagnetic energy into heat energy. However, the food can hardly absorb microwave energy and convert it into heat when the loss factor is too low. This phenomenon is called microwave "transparency." Besides the moisture content, other factors such as metal ion concentration, salt concentration, and food density synergistically affect the dielectric properties as well [19].

3.1.5 Heating uniformity

Heating uniformity is of vital importance for MVP process. Local overheating may occur due to poor heating uniformity, which could affect the taste and color of the products [18]. James et al. [23] studied microwave heating of liquids (water, sauces), solids (mashed potatoes), and multi-component foods (mashed potatoes and spices). Results showed a 22.2°C temperature difference in water spots and 55.1°C in multi-component foods. Thus, multi-component foods have poorer heating uniformity than water. In addition to the composition of food, the geometry and thickness also affect the heating uniformity of food. Nohemí et al. [24] compared the temperature distribution of microwave heating in different shapes (sphere, cylinder, and slab) and sizes (180 and 290 g) of agar gel. Results showed the flat plate heated more uniformly than others, and larger-sized foods were not conducive to internal heating due to microwave penetration depth.

3.2 Products Quality

The quality of puffed products is determined by physical parameters (color, shrinkage, porosity, texture) and chemical properties (polyphenol content, antioxidant capacity, volatiles) [25]. Liu et al. [26] found that MVP significantly increased the expansion volume of blue honeysuckle snacks due to the larger internal pores compared to traditional hot-air drying, as shown in Fig. 3. The porous structure improved crispness. MVP was carried out in a vacuum with rarefied oxygen content for a short time, resulting in a low degree of browning and bright color.

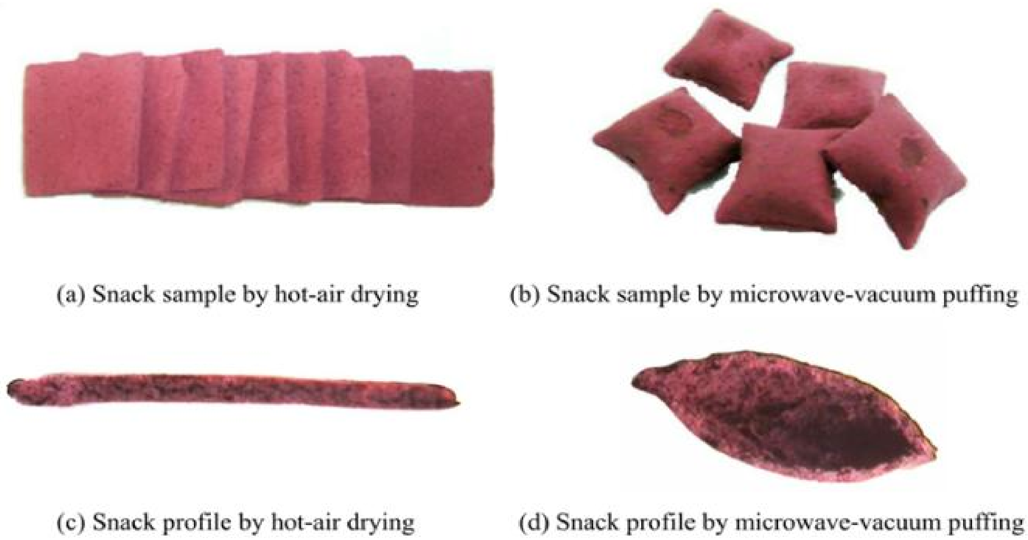

Fig. 3 Appearance and profile of blue honeysuckle snack in different drying [26]

The structure, mechanical deformation, damage fracture resistance, heat and mass transfer, and sound when chewing puffed food depend to a large extent on parameters such as pore size, pore structure, and network skeleton thickness [27]. Liu et al. [28] observed the effects of pulsed microwave-vacuum puffing (PMVP), MVP, and microwave puffing (MP) on the microstructure of shiitake mushrooms. As shown in Fig. 4, compared to MVP, PMVP-treated samples had looser fibers and larger honeycomb spaces, indicating a softer texture. In addition, the dry strawberry experiment [29] showed higher overall evaluation for MVP-dehydrated strawberries than for freeze-dried ones.

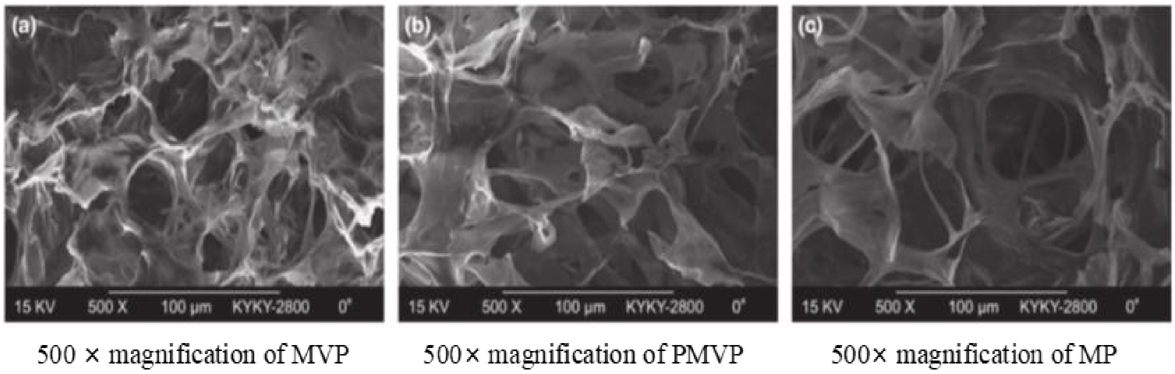

Fig. 4 SEM micrographs of Shiitake mushroom caps puffed using PMVP (a), pulsed microwave-vacuum puffing; MVP (b), microwave-vacuum puffing; MP (c), microwave puffing [3]

Antioxidative properties are also crucial for their preferences and product acceptance. MVP preserves nutrient content and enhances antioxidant capacity. Mu et al. [30] found that the anthocyanin content of raspberry snacks was retained at a high level under microwave power of 2.68 kW and the puffing time of 81 s. The oxygen loss in the vacuum environment contributed to the stability of anthocyanin components in berries. Compared to air drying, freeze-drying, and air pre-drying with explosive puffing, freeze pre-drying followed by MVP better maintains apple probiotic activity at room temperature for over 120 days [31].

Safety is one of the most critical aspects of food quality. Studies have shown that forced carcinogens such as benzopyrene and acrylamide may be produced during high-temperature processing, especially for foods with high oil content [32]. In contrast, researches have shown that the temperature of MVP technology ranges from 50 to 80oC, which did not reach the formation temperature of acrylamide [33].

3.3 Mathematical Simulation in MVP

MVP involves unsteady mass transfer, heat transfer, and volume expansion, which are coupled. Computer simulation models these parameter changes, solves them, and displays results numerically and visually [34].

It is widely accepted that it is difficult to solve the absorption of microwave energy and water evaporation using the dynamic Maxwell equation. Thus, many studies assume microwave energy input is uniform and perpendicular to the material surface. The energy exponentially attenuates, predicting temperature distribution using various analyses or finite element methods. Song et al. [33] studied the MVP model of blackberry, accurately simulating transient heating by combining Maxwell and heat transfer equations, proving the method's accuracy and simplicity. Liu et al. [35] solved the heat transfer in berries by Fourier heat transfer equation combined with dielectric parameter changes. The mathematical model of the temperature field was established using the computer simulation method, with the radius of the fruit as abscissa and the thickness as ordinate. The model accurately fitted the temperature change in the MVP process.

The physical mechanism of mass transfer in MVP process is complex, including water transfer and evaporation. In a vacuum, water inside the sample and reaction chamber can be considered ideal gases. Based on mass conservation, the mass transfer equation can be established [36]. P. Salagnac et al. [37] proposed a hydrothermal behavior model of porous media during microwave heating using a one-dimensional mass and heat transfer model, the finite element software Comsol Multiphysics was used to simulate the distribution of internal water content and temperature in porous media. Shen et al. [38] used Matlab to simulate the water transfer process in blackcurrant microwave vacuum puffing based on the water diffusion equation. The experimental results were in good agreement with the simulation results, which proves that the mathematical model was reliable.

Currently, the materials volume expansion model in MVP is mainly based on the structural mechanics control equation. Ressing et al. [39] established a 2D finite element model to simulate dough puffing during MVP. The model coupled thermal and solid mechanical effects, accurately predicting volume rise at low salt content. A 2D model of raspberry in the MVP process based on the principle of virtual displacement in a quasi-static state was established by Mou et al. [40]. However, the model did not consider stress changes during expansion. Based on the Boltzmann linear superposition principle, Shen et al. [38] determined the whole process of stress and strain in the berry MVP process in the form of genetic integration. The mathematical model established by this method is more accurate and simpler.

4. Future Trends

Over the past fifteen years, much research has been done on MVP technology, especially regarding MVP processing parameters, food quality, puffing kinetics, and processing equipment. Despite advancements, the food industry has been slow to adopt this technology because of

(1) Insufficient research on MVP mechanisms. Most studies focus on process parameter optimization. When raw material or equipment parameters change, the process must be redesigned. Future research should investigate the physicochemical interactions (radiation-food) of basic components like protein, starch, pectin, gas barriers, and product texture to better understand chemical changes and reactions during the MVP process.

(2) The MVP process is accompanied by changes in microwave energy, temperature, pressure, moisture, and volume, but there are few studies on it. Establishing a coupled mathematical model of the electromagnetic field, heat transfer, pressure, and water fields can predict behavior and controllability. The dielectric properties of materials change dynamically due to factors like temperature, moisture content, and porosity. Establishing a dynamic model of dielectric properties and developing real-time feedback applications can help control process parameters and adjust processing modes dynamically.

(3) Non-uniform heating remains a critical issue in the food industry of MVP technology. The key to this problem lies in the good distribution of microwaves in the resonator and food. Therefore, improving MVP equipment designs, such as reflective shields, rotating plates, and cylinders, is crucial to avoid complex resonance electromagnetic field dynamics.

(4) Although most nutrients are retained during MVP, the degradation of components like Vitamin C needs exploration. Reducing nutrient loss and better preserving nutrients must be addressed.

5. Conclusion

MVP is one of the most effective and straightforward puffing methods, producing high-quality products while retaining most nutrients, which is different from other traditional puffing processes. This review has introduced in detail the principles and influencing factors of MVP technology, product quality, and the correlation between process parameters and the physical and chemical properties of products. The Sigmold model effectively fits the expansion behavior of samples like berry chips in MVP. Mathematical simulation accurately describes and explains food behavior in the MVP system. Considering the complex expansion process, the electromagnetic field, heat transfer field, water field, and pressure field should be coupled to simulate the MVP process more accurately based on the dynamic dielectric model. The evolution of MVP equipment was also introduced, from static systems for research to rotating systems that ensure uniform movement of food to improve the problem of uneven temperature distribution. However, further research on the mechanisms and equipment of MVP technology is needed to enhance health-promoting properties and sensory attributes of food products.

Acknowledgment

The authors are grateful to the National Natural Science Foundation of China (Grants No. 31871819) and the regional talent development project of Shanxi Province's "Special Support Program for High-level Talents."

Conflict of interest

There are no conflicts of interest to declare

Appendices

Table 1. A summary of recent research related to the optimal parameter combination and expansion rate of animal and plant foods processed by MVP

Food material (Plant)	IMC (initial moisture content)	Pressure	Microwave intensity	Puffing ratio	reference
Strawberry	24%	4 kPa	9.33 W/g	191.2%	Krulis et al. (2005) [41]
Apple chips	37.5%	15 kPa	12.0 W/g	321%	Han et al. (2006) [42]
Blue honeysuckle snacks	38.42%	82.02 kPa	22.42 W/g	162%	Liu et al. (2010) [43]

Blackcurrant snack	35.59%	23 kPa	9.5 W/g		Mu et al. (2010) [44]
Blackcurrant's chip	35%	30 kPa	20 W/g		Liu et al. (2011) [45]
Blackcurrant Leather	35%	70 kPa	7.03 W/g	200%	Liu et al. (2012) [46]
Berry fruit snack	20%	30 kPa	28 W/g	630%	Zheng et al. (2012) [47]
Black radish	39%	14.5 kPa	43.3 W/g	184%	Pawlak et al. (2013) [48]
Maitake slices	40%	70 kPa	150 W/g	180%	Liu et al. (2016) [49]
Hawthorn tablets	35%	74 kPa	31 W/g	166.3%	Yao et al. (2016) [50]
Bighead carp	19.8%	90 kPa	137.2 W/g	160%	Zhang et al. (2006) [51]
Salted duck egg white/starch products	12%	90 kPa	14.94 W/g	270%	Wang et al. (2016) [52]
Duck breast	59—63%	80 kPa	20.5—24.7 W/g		Wu et al. (2017) [53]

References

[1] Swarnakar, A. K., Mohapatra, M., & Das, S. K. (2022). A review on processes, mechanisms, and quality influencing parameters for puffing and popping of grains. Journal of Food Processing and Preservation, 46(10), e16891.

[2] Daisha, Q., & Qing, Z. (2021). Progress in research on formation mechanism and control methods for acrylamide and heterocyclic amines during food frying. Food Science, 42(21), 338-346.

[3] Suwen, L., Lijie, L., Pengbao, S., & Xuedong, C. (2014). Optimising pulsed microwave-vacuum puffing for Shiitake mushroom (Lentinula edodes) caps and comparison of characteristics obtained using three puffing methods. International Journal of Food Science & Technology, 49(9), 2111-2119.

[4] Zheng, X., Liu, C., Shi, J., Xue, S., Mu, Y., Lin, Z., & Liu, H. (2013). Analysis of volume expansion and dehydration rate of berry slab under microwave-vacuum puffing conditions. LWT - Food Science and Technology, 52(1), 39-48.

[5] R., B., D., M., & C., S. (2015). Microwave–vacuum drying of strawberries with automatic temperature control. Food and Bioprocess Technology, 8(2), 266-276.

[6] Robert, P., Heiko, B., & K., D. A. (2020). Understanding puffing in a domestic microwave oven. Journal of Food Process Engineering, 43(7), e13429.

[7] Haihong, W., Zhengdao, Z., Xinxiao, Z., Huan, B., Daoying, W., & Yongzhi, Z. (2017). Optimization of processing parameters for microwave vacuum puffing of duck breast after hot-air dehydration. Food Science,38(06),267-273.

[8] Anli, E. A. (2020). Possibilities for using microwave-vacuum drying in Lor cheese production. International Dairy Journal, 102, 104618.

[9] Wanxiu, X., Guanyu, Z., Chunfang, S., Shaogang, H., & Zhenfeng, L. (2018). Optimization of microwave vacuum drying and pretreatment methods for polygonum cuspidatum. Mathematical Problems in Engineering, 2018, 4967356.

[10] Tomasz, P., Antoni, R., & Idzi, S. (2013). Optimization of process parameters for microwave-vacuum puffing of black radish slices using the response surface method. Acta scientiarum polonorum. Technologia alimentaria, 12(3), 253-262.

[11] Jinfeng, B., Chunlin, S., Qinqin, C., Xuan, L., Xinye, W., & Xu, S. (2014). Study on optimization of combined hot-air microwave vacuum drying technology for blueberries. Chinese Journal of Food Science, 14(10), 92-100.

[12] D, C. C., E, M.-M., S, W., & E, P. V. (2007). Improving grape quality using microwave vacuum drying associated with temperature control. Journal of Food Science, 72(1), E023-E028.

[13] Haijun, L., Chenghai, L., Xianzhe, Z., & Zhen, L. (2012). Puffing characteristics of blackcurrant leather under microwave vacuum conditions. International Journal of Food Engineering, 8(2), 1168-1174.

[14] Zheng, X., Liu, C., Mu, Y., Liu, H., Song, X., Lin, Z., . . . Weerasooriya, G. V. T. V. (2012). Analysis of puffing characteristics using a sigmodal function for the berry fruit snack subjected to microwave vacuum conditions. Drying Technology, 30(5), 494-504.

[15] Liu, S., Tian, X., Yao, Y., & Chang, X. (2016). Effects of puffing and dehydration of maitake (grifola frondosa) slices by pulsed-microwave vacuum puffing. Advance Journal of Food Science and Technology, 12(7), 352-361.

[16] Wang, T., Zhang, M., Fang, Z., & Liu, Y. (2016). Effect of processing parameters on the pulsed-spouted microwave vacuum drying of puffed salted duck egg white/starch products. Drying Technology, 34(2), 206-214.

[17] Haijun, L., Weijun, Y., Xingduo, F., Weipeng, Y., Xianzhe, Z., & Vijaya, R. (2018). Crispness form of the berry snacks subjected to microwave vacuum puffing conditions. International Agricultural Engineering Journal, 27(3), 230-240.

[18] Luis, G.-C., Mario, P.-W., Gipsy, T.-M., Erick, J.-Q., Rodrigo, D.-Á., & Roberto, L.-M. (2021). Advances in vacuum microwave drying (VMD) systems for food products. Trends in Food Science & Technology, 116, 626-638.

[19] Chandrasekaran, S., Ramanathan, S., & Basak, T. (2013). Microwave food processing—A review. Food Research International, 52(1), 243-261.

[20] E, S.-M. M., L, V.-J., A, L.-M., & S, G. H. (2010). Dielectric properties of foods: Reported data in the 21st Century and their potential applications. LWT - Food Science and Technology, 43(8), 1169-1179.

[21] Al, F. A., Min, Z., & Dongcui, F. (2019). Modeling the dehydration and analysis of dielectric properties of ultrasound and microwave combined vacuum frying apple slices. Drying Technology, 37(3), 409-423.

[22] Xiaotong, M., Guiyi, L., Zhenfeng, L., V., R. G. S., Haiying, C., & Chunfang, S. (2021). Microwave power control scheme for potatoes based on dielectric loss factor feedback. Journal of Food Engineering, 288, 110134.

[23] James, C., Swain, M. V., James, S. J., & Swain, M. J. (2002). Development of methodology for assessing the heating performance of domestic microwave ovens. International Journal of Food Science & Technology, 37(8), 879-892.

[24] Nohemí, S.-R., L, T.-P. A., Aurelio, L.-M., Roberto, R.-L., & Elena, S.-M. M. (2015). Effects of shape and size of agar gels on heating uniformity during pulsed microwave treatment. Journal of Food Science, 80(5), E1021-E1025.

[25] Zapana, F., de Bruijn, J., Vidal, L., Melín, P., González, M. E., Cabrera, G., . . . Bórquez, R. (2020). Physical, chemical and nutritional characteristics of puffed quinoa. International Journal of Food Science & Technology, 55(1), 313-322.

[26] Chenghai, L., Xianzhe, Z., Shuhua, J., Ningye, D., & Xiaochen, G. (2009). Comparative experiment on hot-air and microwave-vacuum drying and puffing of blue honeysuckle snack. International Journal of Food Engineering, 5(4).

[27] Xiaoping, F., Yajun, W., Zijue, Z., Fangying, W., & Danyang, Y. (2018). A review on explosion puffing technology for fruits and vegetables. International Journal of Food Engineering, 4(4), 332-336.

[28] Tian, Y., Zhao, Y., Huang, J., Zeng, H., & Zheng, B. (2016). Effects of different drying methods on the product quality and volatile compounds of whole shiitake mushrooms. Food Chemistry, 197, 714-722.

[29] Jolanta, K., Hanna, K., Agata, M., Tomasz, B., Kinga, S., & Andrzej, L. (2018). Dried strawberries as a high nutritional value fruit snack. Food Science and Biotechnology, 27(3), 799-807.

[30] Yanqiu, M., Xinhuai, Z., Bingxin, L., Chenghai, L., & Xianzhe, Z. (2013). Influences of microwave vacuum puffing conditions on anthocyanin content of raspberry snack. International Journal of Agricultural and Biological Engineering, 6(3), 80-87.

[31] Li, C., Liying, N., Dajing, L., Chunquan, L., Yingping, L., Chunju, L., & Jiangfeng, S. (2018). Effects of different drying methods on quality, bacterial viability and storage stability of probiotic enriched apple snacks. Journal of Integrative Agriculture, 17(1), 247-255.

[32] Taehoon, L., Hyesung, P., Pradeep, P., Gwihee, K., Jungro, Y., & Chulkyoon, M. (2020). Degradation of benzopyrene and acrylamide in roasted coffee beans by corona discharge plasma jet (CDPJ) and its effects on biochemical and sensory properties. Food Chemistry, 328, 127117.

[33] Chunfang, S., Tao, W., Zhenfeng, L., Jing, L., & Haiying, C. (2018). Analysis of the heat transfer characteristics of blackberries during microwave vacuum heating. Journal of Food Engineering, 223, 70-78.

[34] Krzysztof, L., Adam, F., Aneta, W., Małgorzata, K., Małgorzata, S., & Marian, S. (2015). Drying kinetics and bioactivity of beetroot slices pretreated in concentrated chokeberry juice and dried with vacuum microwaves. Drying Technology, 33(13), 1644-1653.

[35] Haijun, L., Zhen, L., Xianzhe, Z., Chenghai, L., Xiangyu, S., & Daiya, L. (2012). Temperature simulation of berry slices under microwave vacuum puffing conditions. Journal of Northeast Agricultural University (English Edition), 19(4), 75-78.

[36] Rakesh, V., & Datta, A. K. (2013). Transport in deformable hygroscopic porous media during microwave puffing. AIChE Journal, 59(1), 33-45.

[37] P, S., P, G., & D, L. (2004). Numerical modeling of heat and mass transfer in porous medium during combined hot air, infrared and microwaves drying. International Journal of Heat and Mass Transfer, 47(19), 4479-4489.

[38] Huifang, S. (2014). Experimental research of blackcurrant berry under ultrasonic-enhanced osmotic dehydration and micrawave vacuum method. (Master Ph.D. Dissertation). Northeast Agriculture University, Harbin, China.

[39] Ressing, H., Ressing, M., & Durance, T. (2007). Modeling the mechanisms of dough puffing during vacuum microwave drying using the finite element method. Journal of Food Engineering, 82(4), 498-508.

[40] Mou, Y. (2011). Study on technology of puffed raspberry snack by using microwave vacuum method and simulation of puffing process. (Ph.D. Dissertation). Northeast Agricultural University, Harbin, China. ProQuest Dissertations & Theses Global database.

[41] Mario, K., Stephan, K., Matthias, L., & Harald, R. (2005). Influence of energy input and initial moisture on physical properties of microwave-vacuum dried strawberries. European Food Research and Technology, 221(6), 803-808.

[42] Qinghua, H., Shujun, L., Jiwei, M., & Donglin, Z. (2006). Microwave vacuum drying and puffing characteristics of apple chips. Transactions of the Chinese Society for Agricultural Machinery, 37(8), 155-158+167.

[43] Chenghai, L., Xianzhe, Z., John, S., Jun, X., Yubin, L., & Shuhua, J. (2010). Optimising microwave vacuum puffing for blue honeysuckle snacks. International Journal of Food Science & Technology, 45(3), 506-511.

[44] Yanqiu, M., Chenghai, L., Xianzhe, Z., & Changjiang, J. (2010). Effects of microwave vacuum puffing conditions on the texture characteristics and sensory properties of blackcurrant (Ribes nigrum.L) snack. International Agricultural Engineering Journal, 19.

[45] Chenghai, L., & Xianzhe, Z. (2011). Comparative experiment of color and structure on microwave and microwave-vacuum puffing of blackcurrant's chip. Paper presented at the 2011 International Conference on New Technology of Agricultural.

[46] Haijun, L., Chenghai, L., Xianzhe, Z., & Zhen, L. (2012). Puffing characteristics of blackcurrant leather under microwave vacuum conditions. International Journal of Food Engineering, 8(2), 1168-1174.

[47] Zheng, X., Liu, C., Mu, Y., Liu, H., Song, X., Lin, Z., . . . Weerasooriya, G. V. T. V. (2012). Analysis of puffing characteristics using a sigmodal function for the berry fruit snack subjected to microwave vacuum conditions. Drying Technology, 30(5), 494-504.

[48] Tomasz, P., Antoni, R., & Idzi, S. (2013). Optimization of process parameters for microwave-vacuum puffing of black radish slices using the response surface method. Acta scientiarum polonorum. Technologia alimentaria, 12(3), 253-262.

[49] Liu, S., Tian, X., Yao, Y., & Chang, X. (2016). Effects of puffing and dehydration of maitake (grifola frondosa) slices by pulsed-microwave vacuum puffing. Advance Journal of Food Science and Technology, 12(7), 352-361.

[50] Yuan, Y., Suwen, L., Cong, L., Xuedong, C., & Quan, H. (2016). Optimization of fermentation conditions for vacuum microwave puffing hawthorn piece. Science and Technology of Food Industry, 37(14), 227-232.

[51] Zhang, J., Zhang, M., Shan, L., & Fang, Z. (2007). Microwave-vacuum heating parameters for processing savory crisp bighead carp (Hypophthalmichthys nobilis) slices. Journal of Food Engineering, 79(3), 885-891.

[52] Wang, T., Zhang, M., Fang, Z., & Liu, Y. (2016). Effect of processing parameters on the pulsed-spouted microwave vacuum drying of puffed salted duck egg white/starch products. Drying Technology, 34(2), 206-214.

[53] Haihong, W., Zhengdao, Z., Xinxiao, Z., Huan, B., Daoying, W., & Yongzhi, Z. (2017). Optimization of processing parameters for microwave vacuum puffing of duck breast after hot-air dehydration. Food Science, 38(06), 267-273.