Application of novel microwave-assisted vacuum frying to reduce the oil uptake and improve the quality of potato chips

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ABSTRACT: The objective of this study was to evaluate the ability of microwave-assisted frying (MVF) technology to reduce the oil uptake and improve quality attributes of fried potato chips. Potato chips were produced using MVF and vacuum frying (VF) technologies and the oil uptake, residual moisture content, microstructure, texture (crispness) and color attributes of chips were compared. The effects of microwave power density (12, 16 and 20 W/g), frying temperature (100, 110 and 120℃) and vacuum degree (0.065, 0.075 and 0.085 MPa) in MVF were evaluated. Results showed that the oil uptake in MVF samples was significantly lower than VF samples, decreased from 39.14 to 29.35 g oil/100 g dry solid. The moisture evaporation rates were accelerated and the MVF produced crispier chips with better natural color. Higher microwave power densities resulted in faster water evaporation rates and lower breaking force. Higher frying temperature led to faster water evaporation, lower oil content and faster color change. Higher vacuum degree bring about faster water evaporation, lower oil content and less color change. Observation of microstructure showed that the cellular structure and integrity of cell wall in chips was better preserved by MVF.

Keywords: Microwave-assisted vacuum frying; potato chips; oil uptake; texture; color

1. Introduction

The retail sales of potato chips represents 33% of total sales of snack in the US Market (Mellema, 2003). Potato chips have an oil content that ranges from 35.3% to 44.5% w.b. and gives the product a unique texture-flavor combination that makes them so desirable(Garayo & Moreira, 2002; Mellema, 2003). In recent years, due to consumer preference for low-fat and fat-free products, considerable research has been concentrated on developing methods that reduce oil absorption in fried products. Many food manufacturers are putting efforts to produce fried potatoes containing less oil at the same time possessing desirable texture and flavor. Vacuum frying (VF) is one of the new methods applied to produce fried fruits and vegetables with low oil content and while still possessing desired texture and flavor characteristics(Andres-Bello, Garcia-Segovia, & Martinez-Monzo, 2011 ; Shyu, Hau, & Hwang, 1998). In this method, fruits and vegetables are fried at low atmospheric pressures, notably below 6.65 kPa which lowers the boiling point of frying oil and water in the samples and ultimately produces fried products with superior sensory and nutritional qualities (Shyu et al., 1998). But it also has the problem of high oil content, so methods for reducing oil absorption in fried products are being researched. The effects of pretreatment and post-treatment on the oil uptake of vacuum fried products have been studied (Fan, Zhang, & Mujumdar, 2006; Sothornvit, 2011). The effectiveness of a two-stage frying process in reducing the oil uptake in the fried potato chips has also been studied (Ravli, Silva, & Moreira, 2013).

Microwave (300 MHz to 300 GHz) can heat dielectric materials by inducing molecular vibration as a result of dipole rotation or ionic polarization (Gharachorloo, Ghavami, Mahdiani, & Azizinezhad, 2009). In many cases microwave heating is more effective heating method compared to conventional methods as it generates heat within the product and the heating time is shorter (Gharachorloo et al., 2009). Microwave heating is broadly and commonly used in food preparation owing to its above mentioned advantages (Buffler, 1993; Cerretani, Bendini, Rodriguez-Estrada, Vittadini, & Chiavaro, 2009; Chandrasekaran, Ramanathan, & Basak, 2013; Ramaswamy & Tang, 2008). It has been shown that application of microwave as a heating source in the frying process produces high quality products and saves energy. For instance, Barutcu et al. (Barutcu, Sahin, & Sumnu, 2009) investigated the effects of microwave frying and various flour types on microstructure of batter coatings. The results showed that microwave fried samples had lower bulk density and higher porosity values and also smoother inner surface as compared to conventionally fried samples. Reports also suggested that the microwave heating pretreatment when combined with vacuum frying greatly improved in the quality of fried potato(Song, Zhang, &Mujumdar, 2007; Song, Zhang, &. Mujumdar, 2007).

Microwave-assisted vacuum frying (MVF) is a special vacuum frying process in which microwave is used as heating source (Su, Zhang, & Zhang, 2015). The intention of applying microwave during vacuum frying is to lower the frying temperature, so that fried products with less oil and better quality can be produced(Su et al., 2015). This work aimed at investigating the possibility of reducing oil uptake and improving the quality of potato chips by the application of novel MVF. The effects of different microwave power (12, 16 and 20 W/g), frying temperature (100, 110 and 120℃) and vacuum degree (0.065, 0.075 and 0.085 MPa)were tested in the experiment. The quality parameters such as oil uptake, drying rate, textural firmness, color and microstructure of potato chips fried in MVF were investigated. These parameters were compared with those of chips produced using VF. The difference in microstructure of samples prepared by MVF and VF has also been discussed by comparing the scanning electron microscope micrographs of the potato chips.

2. Materials and Methods

2.1. Preparation of Materials

Fresh potato and palm oil were purchased from a local supermarket in Wuxi, China. The potato samples were stored at 4℃ in a refrigerator until used in the experiments. No potato sample was used after 5 days of storage. The initial moisture content of potato samples was 82.36 ±1.34 g/100g as measure by the oven method (AACC, 1986). Fresh potatoes were washed, peeled, and sliced about 2±0.2 mm thick. A circular cutting mold was used to produce uniform slices of 36±2 mm in diameter. These slices were blanched in water at 92℃ for 3 min, cooled under running tap water for 1 min, then drained on absorbent paper until the surface was nearly dry. These slices were frozen in a refrigerator at -18℃ for 24 h before use.

2.2 Microwave-assisted vacuum frying

The MVF instrument used in this study has been previously used and described by Su et al.(Su et al., 2015). Three microwave devices are uniformly located around the vacuum chamber and the maximum power output of each microwave source is 1200 W (2450 MHz). The maximum vacuum attainable in this instrument is 0.095 MPa. This MVF was also equipped with a centrifugal separator (Taibang Electromotor Industry Co., Ltd, zhejiang, China) to remove the excess oil from the surface of the potato chips after frying. Experiments were carried out at different power levels (12, 16 and 20 W/g) at a fixed temperature 100℃ (0.085±0.002 MPa,) and at three different temperatures (100, 110 and 120℃) at a fixed power level (20 W/g , 0.085±0.002 MPa) , and three different vacuum degree (0.065, 0.075 and 0.085 MPa) at 100℃ and 20 W/g for 2, 4, 6, 8, 10 min. The oil (5 L) was heated first at different microwave power to achieve target temperature. A batch of 50 g potato chips was fried in each test. The fried chips were centrifuged in situ at 300 rpm for 5 min to remove excess oil without breaking the vacuum. Triplicate runs were carried out and the frying oil was changed in each run.

2.3 Vacuum frying

Vacuum-frying experiments were carried out in a VF instrument using the procedure described earlier by Fan et al. and Song et al. (Fan, Zhang, & Mujumdar, 2005; Song et al., 2007) The vacuum fryer (Fig. 1) was equipped with a centrifuge (Nan Feng Company, Wuxi, China). The capacity of vacuum chamber was 15L similar to that of the MVF. The maximum attainable temperature and vacuum degree of this equipment were 150℃ and 0.095 MPa, respectively. The heating power of VF was 4000 W. A batch of 50 g potato chips was fried in 5 L of palm oil at the same vacuum degree as in the MVF (0.085±0.002 MPa, 100±2℃) for at various time intervals (2, 4, 6, 8, 10 min). After frying, the slices were centrifuged in situ at 300 rpm for 5 min without breaking the vacuum in order to remove excess frying oil.

2.4 Analytical of quality parameters

2.4.1 Moisture Content

The residual moisture content of the samples was determined by using an oven method. Approximately 3 g of samples were oven-dried at 102±3℃ until the mass was stabilized (AACC, 1986). These tests were performed in duplicate.

2.4.2 Oil uptake

The oil content was determined by Soxhlet extraction method with petroleum. (AACC, 1986) Each extraction run was carried out for 8 h. Samples were crushed and oven dried at 102±3℃ to a constant mass. Then, the dried samples were transferred to a single walled cellulose extraction thimble and the oil was extracted gravimetrically using a Soxhlet extraction system for 8 h. (AACC, 1986) The flask containing oil was dried to constant mass in a vacuum dryer at 55℃. The oil uptake in the sample was expressed as g oil/100 g dry mass of the sample. Analyses were carried out in duplicate.

2.4.3 Texture

A texture analyzer (TA-XT2i, Stable Micro System Co. Ltd., Surrey, UK) was used to evaluate the texture of the fried samples. The potato chip was placed over the end of a hollow cylinder and was compressed using a stainless steel spherical probe (P/0.25 s). The pre-speed, test-speed, and post-speed were 2.0, 5.0, and 10.0 mm/s, respectively. The deformation ratio in these tests was maintained at 50% (Su et al., 2015). T he trigger force was 5 g. The force-time curve was recorded and analyzed (expressed in grams) using the software Texture Exponent 32 (StableMicro Systems, Ltd. verson 6.06) associated with the texture analyser. The parameters used to describe the texture of the samples were hardness, defined as the peak force observed at the maximum compression (Steffe, 1996). All the samples were kept in the individual sealed bags and placed in the desiccator to avoid the absorption of the humidity from the environment. The textural hardness was measured immediately after the sample preparation. Five chips were tested and the hardness value was average of these 5 chips.

2.4.4 Color

The color parameters of samples were measured using a chroma meter (CR-400, Konica Minolta Sensing, Inc., Osaka, Japan). The samples were placed in a standard light and the Hunter L* (lightness), a* (redness), and b* (yellowness) values were measured. The L*, a*, and b*values of the unfried potato slices were L^*_0 (72.11±0.43), a^*_0 (-4.95±0.20), b^*_0 (21.15±0.87), respectively. Three slices or chips obtained at each condition were tested and three readings were taken at different positions for a potato chip and all the data points were averaged. The total color difference (ΔE) was calculated from the differences of L*, a*, and b* of the unfried potato slices and fried chips using the following equation (1) (Figiel, 2009; Wang, Zhang, & Mujumdar, 2011), given below.

$$\Delta E = [(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2]^{1/2} \quad (1)$$

Where, L^*_0, a^*_0, b^*_0 are the L*, a*, and b*values of the fresh potato slices respectively.

2.5 Observation of surface morphology of fried chips

For observation of surface morphology of the chips, their oil content was first removed using petroleum ether. The oil extract chips samples were placed on one surface of a two-sided adhesive tape that was fixed to the sample support. Finally, chips samples were mounted on aluminum stubs, coated with gold (CPD-030, BAL-TEC Company, Liechtenstein) under vacuum condition, and then observed on a Quanta-200 scanning electron microscope (SEM, Quanta-200, FEI, Netherlands). An accelerating voltage of 5 kV was used in these tests. The samples used in these tests were prepared using MVF (1000 W, 100℃, 0.085 MPa, 10 min) and VF (100℃, 0.085 MPa, 10 min).

2.6 Statistical Analysis

Statistical analysis was performed using SPSS software for Windows (version 11.5.1 SPSS Inc., Chicago, IL). Differences among product quality attributes were tested for significance was expressed by one-way analysis of variance (ANOVA). A 95% confidence level ($p<0.05$) was used for this purpose.

3. Results and discussion

3.1 The moisture content of potato chips produced by MVF

The effects of different microwave power, frying temperature and vacuum degree on the moisture content of potato chips during MVF are shown in Fig. 2. As can be seen in the Fig. 2(a), the moisture content decreased rapidly with frying time both in the case of MVF and VF samples. Due to the application of microwave energy, the moisture content in MVF samples decreased faster than that in the VF samples. The higher microwave power levels removed the moisture content from the samples faster. In the MVF, the sample absorbed the energy from the microwave in addition to that from the heated oil. The outward diffusion of moisture is also significantly enhanced by the application of microwave (Oztop, Sahin, & Sumnu, 2007). The accelerated moisture removal rate in MVF can be attributed to the distinctive heating mode of the microwave in the MVF. At the beginning of frying, the moisture content in the potato slices is very high and the outward movement of water is mostly through the membrane and cell wall. The kinetic energy of water molecules increased when they absorbed microwave energy and the extent of their vibration increased accordingly. The increased vibration increased the internal friction and the kinetic energy converted into the thermal energy which ultimately caused faster evaporation of water molecules. The coupled heat and mass transfer processes within the sample are rapid during the microwave heating because heat is generated within the sample. (Wang, Xiong, & Yu, 2004) In the case of VF, the water molecule in the surface of the potato chips was heated first the hot oil and then the heat flows from the surface to the interior of the potato chips. Thus there is greater temperature gradient and less driving force for water molecules to evaporate. This is the reason why the moisture removal in MVF was much faster than that in VF under identical processing condition. The amount of removed water at a given time in MVF is much higher than that in VF which is in accordance with published reports which show that the application of microwave sharply shortens the processing time (Ramaswamy & Tang, 2008). As shown in Fig. 2(b), the moisture content decreased faster with the increase in the frying temperature (at a fixed power density) in MVF and the moisture content reached as low as 1.58 g/100g in 6 min at 120℃. It also can be seen in the Fig.2(c) that the rate of dehydrate in MVF is faster with the higher vacuum degree and the rate of dehydrate got the fastest with the 0.085MPa. It was because the higher of the vacuum degree in the MVF will result the lower boiling point of the water and led to the higher drying rate. These observations indicate that the frying temperature, microwave power and vacuum degree are important factors in determining moisture removal rate and the residual moisture content in the fried product.

3.2 The oil content in potato chips produced by MVF

Oil content is one of the most important quality attributes of fried products. Very high oil content usually results into an oily and tasteless product. High oil content in fried product not increases the cost of the processor but also fried products with high oil contents are considered unhealthy. The effects of microwave power level, frying temperature and vacuum degree on the oil content of potato chips are shown in Fig. 3. As can be seen in the Fig. 3(a), the oil content increased with the increase in frying time both in MVF and VF; however, the oil content was significantly ($p<0.05$) lower in MVF chips than in VF chips at the same frying time. For example, the oil content of MVF chips ranged from 29.35 to 31.92 g oil/100 g dry solid and it was 39.14 g oil/100 g dry solid in VF chips at 10 min of frying. Interestingly, when the frying temperature increased (Fig. 3(b)) the oil content of potato chips fried using MVF decreased significantly ($p<0.05$). For example, the oil contents of chips fried at 100℃

and 120℃ were 31.92 and 25.13 g oil/dry solid, respectively. And the oil content of potato chips decreased significantly ($p<0.05$) with the increase of vacuum degree as shown in the Fig. 3(c). The oil content of chips fried at 0.085 MPa were 31.92 g oil/dry solid while it increased to 36.21 g oil/dry solid at 0.065 MPa as showed in the figure. The above observations indicate that the oil content in potato chips can be significantly reduced by replacing VF with MVF by choosing appropriate power level, frying temperature and vacuum degree.

During the frying process of VF, water evaporates very rapidly from the surface of the food which creates a moisture gradient between the surface and the interior. The moisture from the interior of the food diffuses out as steam and creates a pressure gradient. As the moisture content decreases the path required for diffusion increases and the increased solid and/or oil content greatly increase resistant to outward diffusion of moisture. (Bravo, Sanjuán, Ruales, & Mulet, 2009). During the pressurization and cooling steps, the pressure inside the pores changes, thus creating a pressure difference between the surface and the center of the product. This pressure difference generates a driving force for the oil at the surface to penetrate the pores. (Yagua & Moreira, 2011) The uptake of oil occurs mainly during pressurization and cooling stage. (Mir-Bel, Oria, & Salvador, 2009; Yagua & Moreira, 2011) The oil occupies the porous area left vacant by evaporated water and adheres to the dry portion of the chips. Thus, the increase of oil content in potato chips is related to the decrease of moisture content (Gamble, Rice, & Selman, 1987). In the case of MVF, the microwave energy provides additional impetus for water molecules to diffuse outwards rapidly. The unique heating mode of microwave makes less pathways required for moisture diffusion. In the pressurization and cooling steps, the moisture pathway in MVF made less areas for the connection between the dry portion and the oil than VF. As a consequence, the oil uptake became less in MVF in contrast with VF. In general, with the use of MVF, the oil uptake in fried potato chips could significantly decreased contrast with VF.

3.3 The texture of chips fried using MVF

The heat and mass transfer together with chemical reactions occurring in the frying process are responsible developing texture in fried products. (Troncoso & Pedreschi, 2009) The breaking force can be used as an indicator of crispness of vacuum fried potato chips and that the lower the breaking force the higher the crispiness. (Fan et al., 2005) It can be observed in Fig. 4 that the breaking force decreased with the increase in frying time from 4 to 10 min both in MVF and VF. The breaking force of potato chips in the first 4 min of frying was very low due to high moisture content and soft texture. The breaking force of MVF fried samples in 10 min of frying was significantly ($p<0.05$) lower than those fried using VF as shown in Fig. 4. It means the crispness of potato chips is significantly ($p<0.05$) increased by MVF. It also can be seen from Fig. 4(a) that the increase in microwave power level resulted into decrease in breaking force in MVF. This is due to faster moisture evaporation at higher power which produced crispier texture. When the water is evaporated from the potato chips during frying, the oil covers the porous area left vacant by evaporated water and affects the texture. The decrease in moisture content with frying time resulted into increasingly crispier chips. The faster water evaporation rates in MVF created higher pore density in the potato chips which favored formation of crispier texture. The variation of breaking force of potatoes chips during MVF and VF is accordance with the variation of moisture content and oil uptake. As articulated above, a porous texture is expected to increase the crispness in chips. As shown in Fig. 4(b), the breaking force reached its lowest value at shorter time when the frying temperature increased which can be attributed to the faster removal of water and faster oil uptake. However, the magnitude of breaking force at the tested frying temperatures (100,110 and 120℃) was the same indicating that the frying temperature did not significantly ($p>0.05$) affect the crispness of potato within the test range. The effects of vacuum degree on the breaking force during MVF was showed in the Fig. 4(c). It can be observed that higher vacuum degree in MVF produced potato chips with lower breaking force. However, the crispness of potato chips in MVF was not significantly ($p>0.05$) affected by the vacuum degree. The affection of vacuum degree and frying temperature on the texture of potato chips in MVF were in accordance with the frying process of VF in published reports (Garayo & Moreira, 2002).

3.4 The color of MVF

The changes in color of fried samples were observed by analyzing L* (lightness), a*(red-green chromaticity), b* (yellow-blue chromaticity), and ΔE coordinates. The effects of microwave power, frying temperature and vacuum degree on the color of potato chips after frying 10 minutes in MVF and VF were shown in the Table 1. L*is a critical parameter in the frying of food, and is usually used as a quality control parameter (Mariscal & Bouchon, 2008). Higher L* value indicates a lighter color which means more desirable for consumers. As can be seen in the Table 1, the L* value of potato chips fried in MVF is significantly ($p<0.05$) higher than that in VF. The formation of darker color (low L* values) during frying is associated with non-enzymatic browning reactions including Maillard reaction, caramelization, and chemical oxidation (Su et al., 2015). It means that the chips fried using MVF were visually more appealing compared to those fried using VF. It also can be seen from the L* values that there was no significant difference ($p>0.05$) in the lightness of potato chips prepared at different power levels of MVF. This observation agrees with the findings of Swittra et. al who reported the increase in the microwave power intensity did not affect he lightness and yellowness of the durian chips(Bai-Ngew, Therdthai, & Dhamvithee, 2011). The L* values was significantly ($p<0.05$) reduced in higher frying temperatures and lower vacuum degree in MVF. However, these values were still higher than that of VF at the same temperature.

The red-green chromaticity increased considerably in both frying process, changing from negative values (towards green) to positive ones (increasing redness). The redness (a* value) of MVF samples was significantly ($p<0.05$) lower than that of VF samples (Table 1). There was no significant difference ($p>0.05$) in the redness (a* value) of MVF samples obtained using different power density and vacuum degree. A significant higher a* values was obtained with higher temperatures in MVF. This higher a* value can be attributed to the browning reactions occurring during microwave assisted frying. The variation of a* values suggests that the frying temperature is the main factor affecting the redness in potato chips obtained from MVF

The b* values of fried potato chips increased considerably with the frying time in both the frying processes. The b* values of MVF fried potato chips were higher ($p<0.05$) than those of the VF samples (Table 1). It indicated that the potato chips had higher intensity of yellow color when fried in MVF than in VF. A significant ($p<0.05$) increase had been seen in b* values in higher frying temperature and vacuum degree while no significant difference ($p>0.05$) in different power levels of MVF. This observation agree with the finding from Swittra et al who reported that the increase in the microwave power intensity did not affect yellowness of the durian chips (Bai-Ngew et al., 2011).

The total color difference (ΔE) values of MVF samples at the end of frying time (10 min) were significantly ($p<0.05$) lower than those in VF as shown in the Table 1. The deterioration of total color can be attributed to the removal of water and progress in nonenzymatic browning including Maillard reaction and caramelization all of which occur more easily at higher enthalpy (Anese, Nicoli, Massini, & Lerici, 1999; Jiang, Zhang, & Mujumdar, 2010). The lower the values of ΔE, the smaller the total color difference between the un-fried and fried potato chips and better the preservation of natural color. It is worth noting that potato chips retained good color when fried under MVF than in VF. The lower △E values of potato chips was obtained with the lower microwave power level, lower frying temperature and higher vacuum degree in the MVF.

3.5 Microstructure of fried potato chips

Potato chips prepared from MVF had lower oil uptake, lower residual moisture content, crispier texture and better appearance compared to those produced by VF. Hence, it is of interest to investigate the difference in the microstructure of chips prepared by MVF and VF. Fig .5 shows the scanning electron (SEM) micrographs of the surface of MVF potato chips (a, b) and VF potato chips (c, d). The most apparent difference on the micrographs of these two samples is the nature of cellular structure formed after frying. The SEM micrographs of MVF potato chips (a, b) show that most of the cells of potato chips preserved their shape and integrity of cells wall. In contrast, most of the cells of VF potato chips(c, d) appear collapsed and the cell wall appeared damaged and even broken down. The way the mass transfer and moisture evaporation occurred in MVF and VF processes are responsible for these differences in microstructure. Water molecules preferentially absorb microwave energy and become activated. The high kinetic energy of water molecules in MVF enables their fast and easier transfer through the cell and cell wall without causing their collapse. In the case of VF, the heat flux from the heated oil requires to be transferred through the dried or partially dried solid matrix to the interior of the material. Thus the overheating on the outer surface and formation of dryer exterior (and hence slower moisture removal rate) in VF fried chips favor the collapse of cellular structure and integrity of the cell wall especially on the outer surface.

4. Conclusion

Based on the residual moisture content, oil uptake, textural crispness, and color quality, we showed that MVF is better than VF in producing potato chips. The application of MVF significantly reduced the oil uptake, increased the water evaporation rate, reduced the breaking force (made the product crispier) and better preserved the natural color in potato chips. The application of higher microwave power density in MVF, from 12 W/g to 20 W/g, resulted into faster water removal, lower breaking force while no significant difference in oil content and color parameters. Higher frying temperatures led to faster water evaporation, lower oil uptake, faster color change while no significant difference in breaking force. Higher vacuum degree bring about faster water evaporation, lower oil content and less color change while no significant difference in breaking force. A comparison of SEM micrographs of MVF and VF samples shows that the cellular structure and integrity of cell wall of samples were better preserved by MVF than VF. This work concludes that MVF is capable of producing crunchier (lower breaking force), healthier (less oil content) fried products with better color and texture.

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Figure Captions

Fig.1. Schematic diagram of the vacuum frying instrument

Fig.2. Comparisons of moisture content of potato chips during MVF in different power density (a), frying temperature (b) and vacuum degree (c) with VF.

Fig.3. Comparisons of oil uptake of potato chips during MVF in different power density (a), frying temperature (b) and vacuum degree (c) with VF.

Fig.4. Comparisons of breaking force of potato chips during MVF in different power density (a), frying temperature (b) and vacuum degree (c) with VF.

Fig.5. Scanning electron micrographs (80× and 160× magnification) of microwave-assisted vacuum frying potato chips (a, b) and vacuum frying potato chips (c, d).

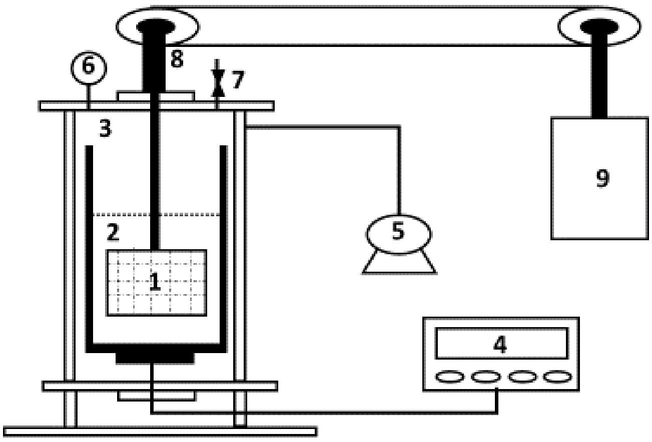
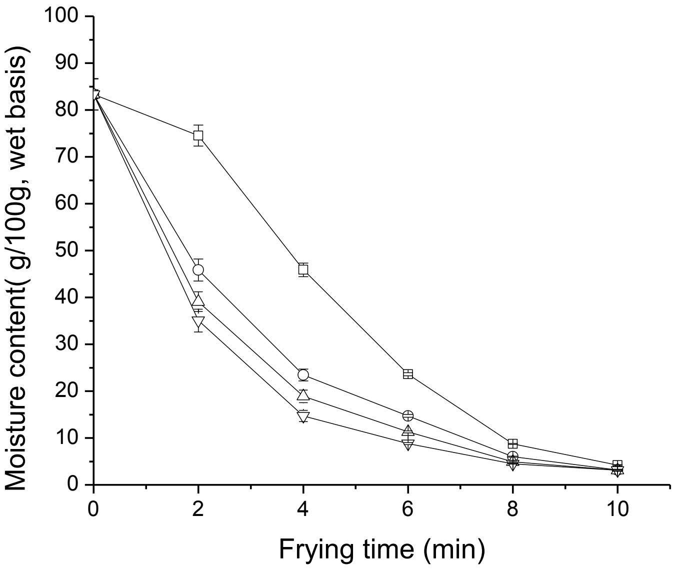
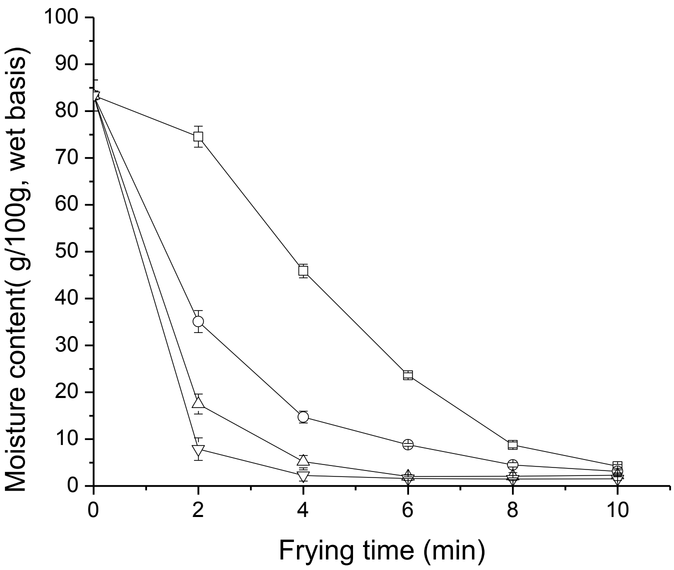


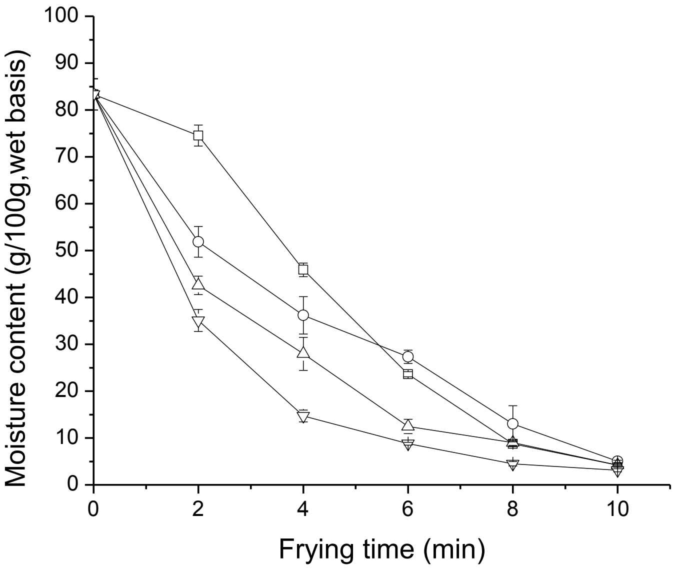
Fig.1. Schematic diagram of the vacuum frying instrument. 1. Frying basket 2. Frying chamber 3. Vacuum chamber 4. Temperature controller 5. Vacuum pump 6. Pressure gauge 7. Valve for breaking 8. Lifting shaft 9. Electric motor


Moisture content(g/100g, wet basis)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
Frying time (min)

(a)

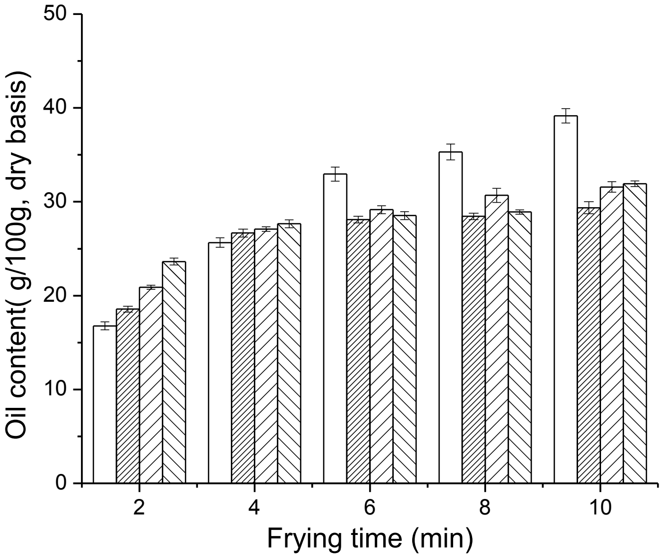

Moisture content(g/100g, wet basis)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
Frying time (min)

(b)

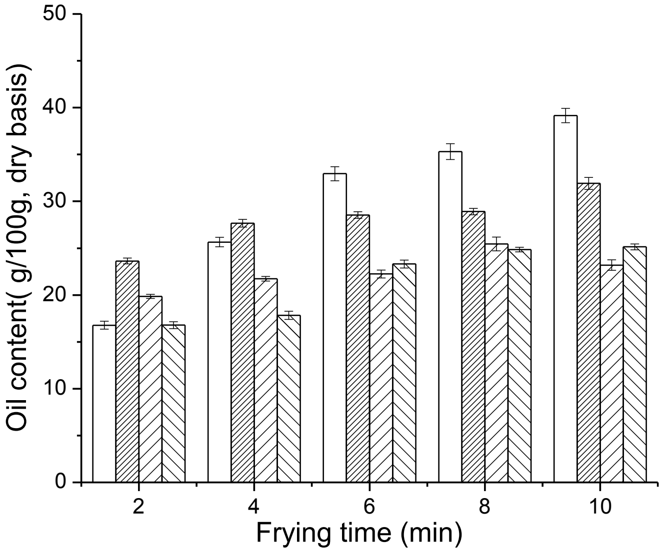


(c)

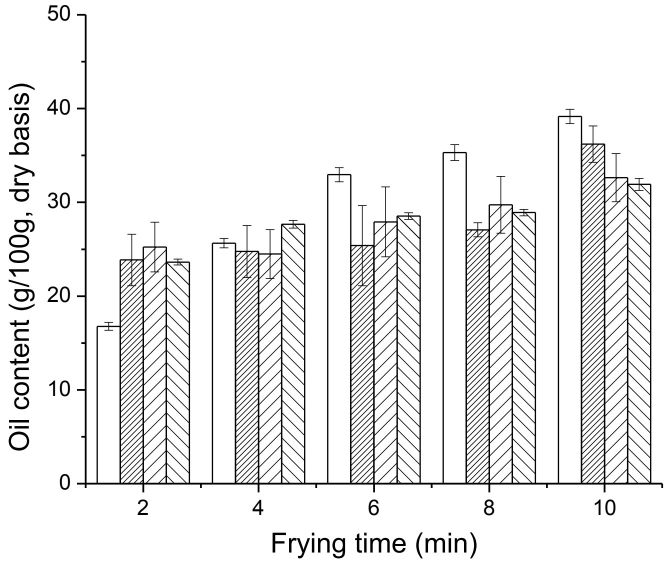
Fig.2. Comparisons of moisture content of potato chips during MVF in different power density (a), frying temperature (b) and vacuum degree (c) with VF. (a) Effect of different microwave power density on the moisture content during MVF（□: VF; ○ : MVF 12 W/g; △ : MVF 16 W/g; ▽: MVF 20 W/g; The frying temperature and vacuum degree is 100℃ and 0.085 MPa）. (b) Effect of different microwave power density on the moisture content during MVF（□: VF 100℃; ○ : MVF 100℃; △ : MVF 110℃; ▽: MVF 120℃; The vacuum degree is 0.085 MPa and the power density in MVF is 20 W/g ）. (c) Effect of different vacuum degree on the moisture content during MVF （□: VF 0.085 MPa; ○ : MVF 0.065 MPa; △ : MVF 0.075 MPa; ▽: MVF 0.085 MPa; The frying temperature is 100℃ and the power density in MVF is 20 W/g）.


Oil content(g/100g, dry basis)
0
10
20
30
40
50
2
4
6
8
10
Frying time (min)

(a)

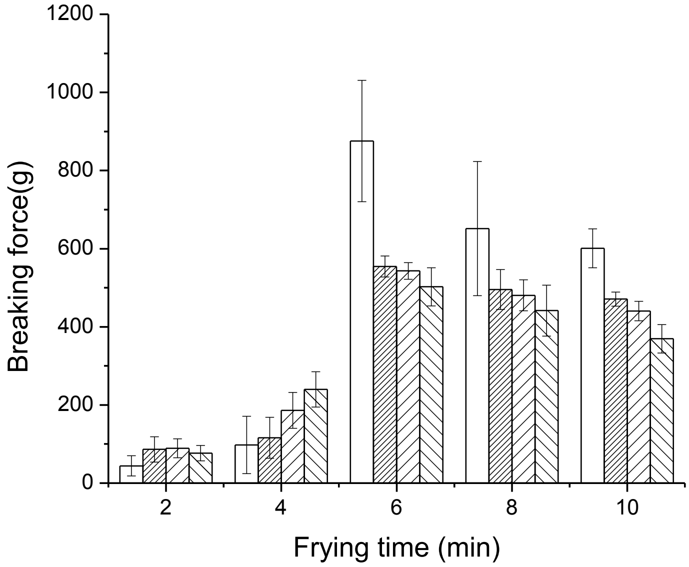

Oil content(g/100g, dry basis)
0
10
20
30
40
50
2
4
6
8
10
Frying time (min)

(b)

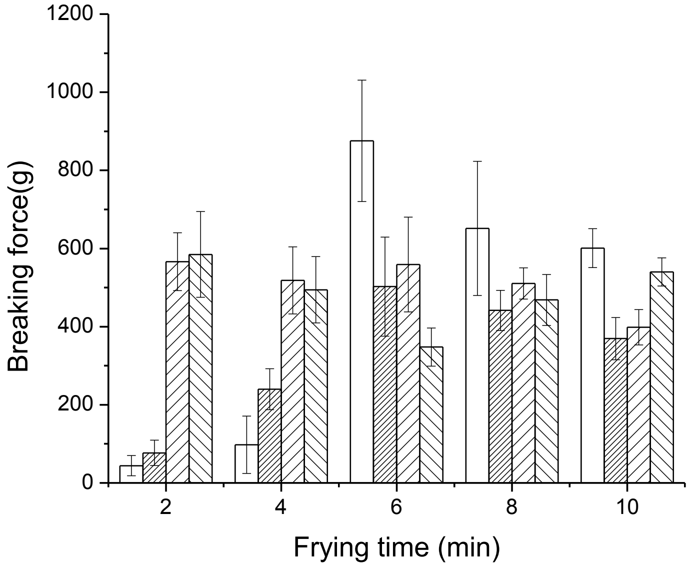


(c)

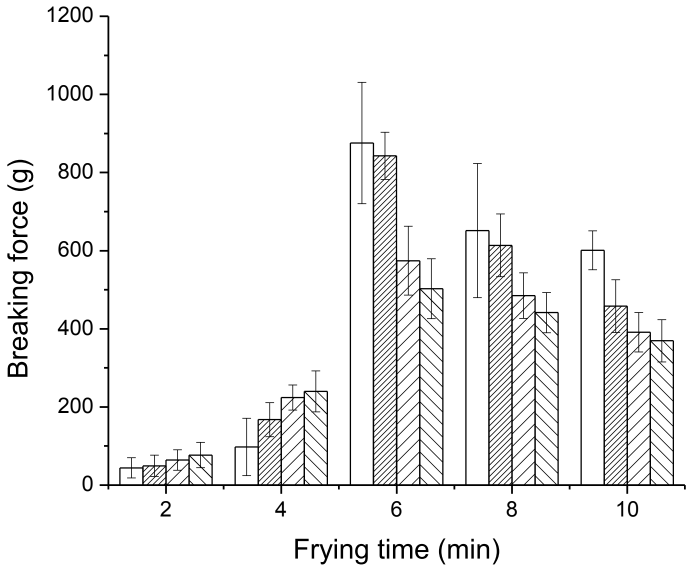
Fig.3. Comparisons of oil uptake of potato chips during MVF in different power density (a), frying temperature (b) and vacuum degree (c) with VF. (a) Effect of different microwave power density on the oil content during MVF (：VF; ：MVF 12 W/g; ：MVF 16 W/g; ：MVF 20 W/g; The frying temperature and vacuum degree is 100℃ and 0.085 MPa）. (b) Effect of different microwave power density on the oil content during MVF (：VF 100℃; ：MVF 100℃; ：MVF 110℃; ：MVF 120℃; The vacuum degree is 0.085 MPa and the power density in MVF is 20 W/g）. (c) Effect of different vacuum degree on the oil content during MVF (：VF 0.085 MPa; ：MVF 0.065 MPa; ：MVF 0.075 MPa; ：MVF 0.085 MPa; The frying temperature is 100℃ and the power density in MVF is 20 W/g）.


Breaking force(g)
0
200
400
600
800
1000
1200
2
4
6
8
10
Frying time (min)

(a)

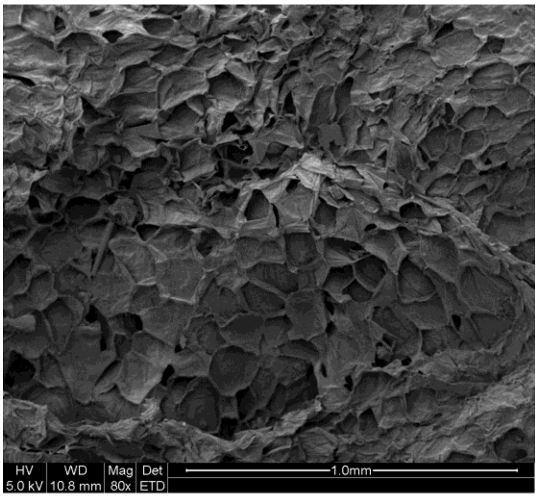

Breaking force(g)
0
200
400
600
800
1000
1200
2
4
6
8
10
Frying time (min)

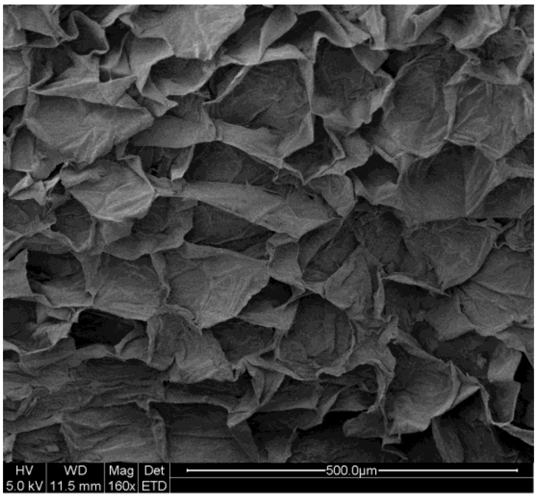
(b)



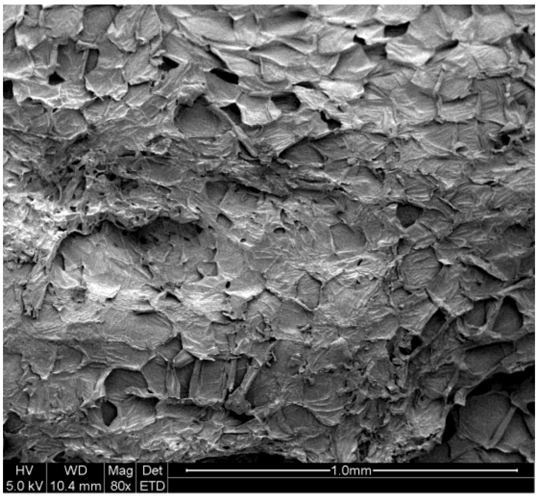
(c)

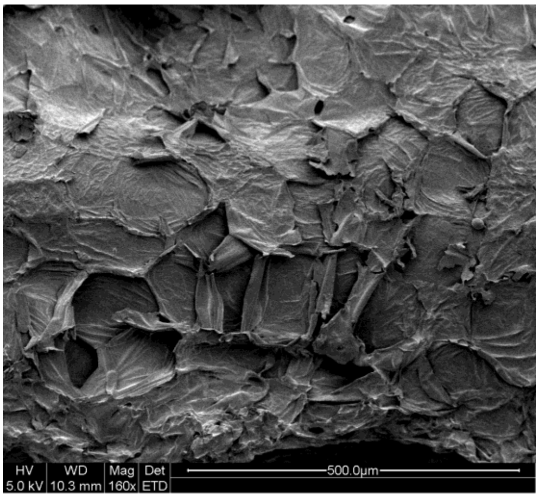
Fig.4. Comparisons of breaking force of potato chips during MVF in different power density (a), frying temperature (b) and vacuum degree (c) with VF. (a) Effect of different microwave power density on the breaking force during MVF (： VF; ： MVF 12 W/g; ： MVF 16 W/g; ： MVF 20 W/g; The frying temperature and vacuum degree is 100℃ and 0.085 MPa）. (b) Effect of different frying temperature on the breaking force during MVF （ ： VF 100℃; ： MVF 100℃; ： MVF 110℃; ： MVF 120℃; The vacuum degree is 0.085 MPa and the power density in MVF is 20 W/g）. (c) Effect of different vacuum degree on the breaking force during MVF (： VF 0.085 MPa; ： MVF 0.065 MPa; ： MVF 0.075 MPa; ： MVF 0.085 MPa; The frying temperature is 100℃ and the power density in MVF is 20 W/g）





(a) (b)





(c) (d)

Fig.5. Scanning electron micrographs (80× and 160× magnification) of microwave-assisted vacuum frying potato chips (a, b) and vacuum frying potato chips (c, d). (a, b): microwave-assisted vacuum frying potato chips, (c, d): vacuum frying potato chips. The magnification was set as ×80 in (a, c) and ×160 in (b, d).

Table 1 The color parameters (L* value, a* value, b* value, ΔE value) of potatoes chips in VF and MVF with different microwave power (12, 16 and 20 W/g), frying temperature (100,110 and 120℃) and vacuum degree (0.065, 0.075 and 0.085 MPa) after frying 10 minutes.

Frying condition	Frying temperature (℃)	Microwave power density(W/g)	Vacuum degree(MPa)	L*	a*	b*	ΔE
VF	100	-	0.085	49.55±2.31	-0.79±0.31	25.64±2.04	23.37±0.32
		12		69.06±1.83	-3.32±0.28	25.21±1.19	5.33±0.17
MVF	100	16	0.085	67.47±1.08	-2.18±0.27	24.49±1.49	6.35±0.28
		20		68.02±0.71	-2.95±0.29	25.97±0.85	6.63±0.30
	100			68.02±0.71	-2.95±0.29	25.97±0.85	6.63±0.30
MVF	110	20	0.085	61.53±5.06	-1.19±2.47	28.75±1.68	14.02±3.92
	120			61.25±7.74	2.87±1.04	30.88±0.80	17.14±7.49
			0.065	57.09±4.40	-3.17±1.14	17.40±1.74	15.61±4.75
MVF	100	20	0.075	64.99±4.88	-3.27±1.03	21.78±3.99	8.13±4.26
			0.085	68.02±0.71	-2.95±0.29	25.97±0.85	6.63±0.30

(Mean valu ±standard deviation)

(VF means vacuum frying，MVF means microwave-assisted vacuum frying)