
APST

Asia-Pacific Journal of Science and Technology<https://www.tci-thaijo.org/index.php/APST/index>Published by Research and Innovation Department,
Khon Kaen University, Thailand

Application of a vertical centrifugation technique to develop a de-oiling machine for crispy fried enoki mushrooms

Thawanrat Sumrit¹, Surintraporn Swaeng-ngam¹, Patcharaporn Inrirai¹, Voraluck Suriwong¹ and Tanakorn Jantarasricha^{2,*}¹ Department of Food Engineering, Faculty of Food and Agricultural Technology, Pibulsongkram Rajabhat University, Phitsanulok 65000, Thailand² Department of Production Engineering Technology, Faculty of Industrial Technology, Pibulsongkram Rajabhat University, Phitsanulok 65000, Thailand

*Corresponding author: tanakorn.ja@psru.ac.th

Received 17 June 2024

Revised 24 June 2024

Accepted 24 April 2025

Abstract

The aim of this research was to develop a de-oiling machine and evaluate its efficiency when making crispy fried enoki mushrooms in terms of reducing residual oil in the product after the frying process. This machine had five essential components: vertical centrifugation, an external tank, a motor unit, oil drainage, and a speed adjustment mechanism. After the frying process, the crispy enoki mushrooms had an average weight of 150 g. The adjustment of the de-oiling speed levels was examined using three different speeds: 6, 7, and 8, while the de-oiling durations were set at 30, 40, and 50 sec. The results revealed that the use of different operating conditions affected the removal of oil. The de-oiling process, conducted at speed level 8 for a duration of 30 sec, resulted in a weight loss of $8.41 \pm 0.72\%$ after the oil removal. The a_w value obtained was 0.32 ± 0.00 , while the hardness value was 30.60 ± 1.46 N. Additionally, the fat content was determined to be $31.32 \pm 1.08\%$. This operation enabled improved textural qualities compared to other conditions. Compared to the control sample, the samples with lower fat content exhibited increased crispiness. Meanwhile, the control sample had a fat content of $45.05 \pm 0.28\%$ and a hardness of 28.36 ± 0.21 N. The efficiency of oil removal from crispy fried enoki mushrooms was enhanced using this developed de-oiling machinery, which ensures that the texture and flavor of these mushrooms are preserved after the frying process.

Keywords: De-oiling, Enoki mushroom, Machine, Vertical centrifugation, Weight yield

1. Introduction

Thailand is a nation mostly focused on agriculture and boasts a wide range of ecosystems suitable for cultivating mushrooms [1]. Currently, mushrooms are cultivated worldwide, with their output seeing significant growth of over thirtyfold and exhibiting a continuous increase in quantity. Enokitake (*Flammulina velutipes*) is a highly abundant type of mushroom whose production is anticipated to have significant growth in the future [2]. Enokitake mushrooms are rich in vitamin B1 and have a low zinc content. This provides benefits to patients diagnosed with hypertension and the elderly population. There is potential for reductions in blood sugar levels, blood pressure, and cholesterol levels. The human body derives benefits from the consumption of polysaccharides, which are dietary fibers [3-5]. Enokitake mushrooms have a delicious, naturally sweet, and aromatic flavor, and the tenderness of the mushroom flesh may be applied to a variety of dishes, such as deep-fried food. The crispy fried texture enhances the overall pleasant taste and flavor.

Frying is a conventional method and widely preferred process in food preparation, providing particular qualities such as flavor, texture, and taste in the fried meal [6]. Deep-fried products tend to be favorites because of their distinctive taste and texture. In both macroscopic and microscopic aspects, deep-fat frying facilitates modifications in the physical and chemical composition of the food. One major issue associated with fried

products is the high amount of oil contained in the final product, which ranges from 35% to 45% [6-7]. Consuming excessive amounts of these dietary items has been linked to several metabolic disorders, resulting in health problems including cardiovascular disease, obesity, elevated cholesterol levels, and hypertension [8-11]. In general, fried snacks consisting of crispy outer layers and soft, moist insides tend to rapidly lose their crisp texture within 3 to 20 min upon cooling [12]. The oil adheres to these foods and is then drawn into the outer layer. The cellular-level crispy texture is influenced by these oils, resulting in a reduction in crispness. However, this does not impact the mechanical qualities of the product. Consequently, its shelf life will be shortened [12]. Nevertheless, an increased understanding among consumers about the relationship between food, nutrition, and health has highlighted the importance of decreasing one's oil consumption. Caloric content is influenced by various components, including fat and cholesterol [13]. Presently, many techniques are used for frying mushrooms. The research conducted by Al Faruq et al. [12] involved the utilization of ultrasound combined with microwave vacuum frying (UMVF), vacuum frying (VF), and deep fat frying for the purpose of frying mushrooms. Following the frying process, the fried mushrooms underwent centrifugation using de-oiling equipment, which effectively removed oil. The utilization of UMVF in frying resulted in a reduction of oil content by approximately 16-20%, whereas the use of VF in frying led to a reduction of up to 18.78% compared to deep fat frying. Despite this, frying requires an extensive financial investment, which may represent an obstacle for small-scale enterprises that need more funds to purchase the appropriate machinery.

Today, mushrooms are processed utilizing deep fat frying techniques due to their cost-effectiveness, making them a popular choice among small-scale enterprises. Deep fat frying is a preparation method wherein food is cooked by causing direct contact between it and edible oil, which serves as the medium for transferring heat at a temperature higher than the boiling point of water. This approach is extensively employed in both industrial and domestic applications. The purpose of applying this technique is to make a product that exhibits unique characteristics in terms of flavor, color, and texture compared with other fried food products [14-16]. Following the frying process, the goods undergo either a period of rest to eliminate oil or are baked in a baking setup in high-temperature conditions to decrease the oil level in the fried food items. Subsequently, the product is packaged for commercialization. Nevertheless, oil can leak from the packaging of fried goods, resulting in an unpleasant odor. This poses a significant issue for small-scale manufacturers in terms of their production costs. As a result, the food quality and nutritional composition of products are impaired. Hence, it would be useful to develop and construct a de-oiling machine specifically designed for frying food items. The de-oiling method involved in making vacuum-fried potato chips, the impact of frying temperature on potato chip quality, and the oil absorption of potato chips have been studied by Moreira et al. [16] The research results indicated that the non-centrifuged samples exhibited bulk density and porosity values of around 800 kg/m^3 and 0.36, respectively. In contrast, the centrifuged samples presented bulk density and porosity values of 564 kg/m^3 and 0.61, respectively. The study conducted by Kim et al. [17] investigated the influence of centrifugation on decreasing the oil content in fried snacks. The results revealed that increasing the frying temperatures, reducing the centrifugal speed, and reducing the cooling time were associated with the lowest oil content in the snacks.

For producing crispy enoki mushrooms, the expected outcome of the frying process is a texture that is crisp and free from any remaining oil. This oil may cause an absence of crispness in the enoki mushroom texture and result in the release of an undesirable smell. Moreover, it is also essential that the fried product is a golden yellow color. Therefore, the objective of this research was to apply a vertical centrifugation technique to develop a de-oiling machine suitable for the application of crispy fried enoki mushrooms.

2. Materials and methods

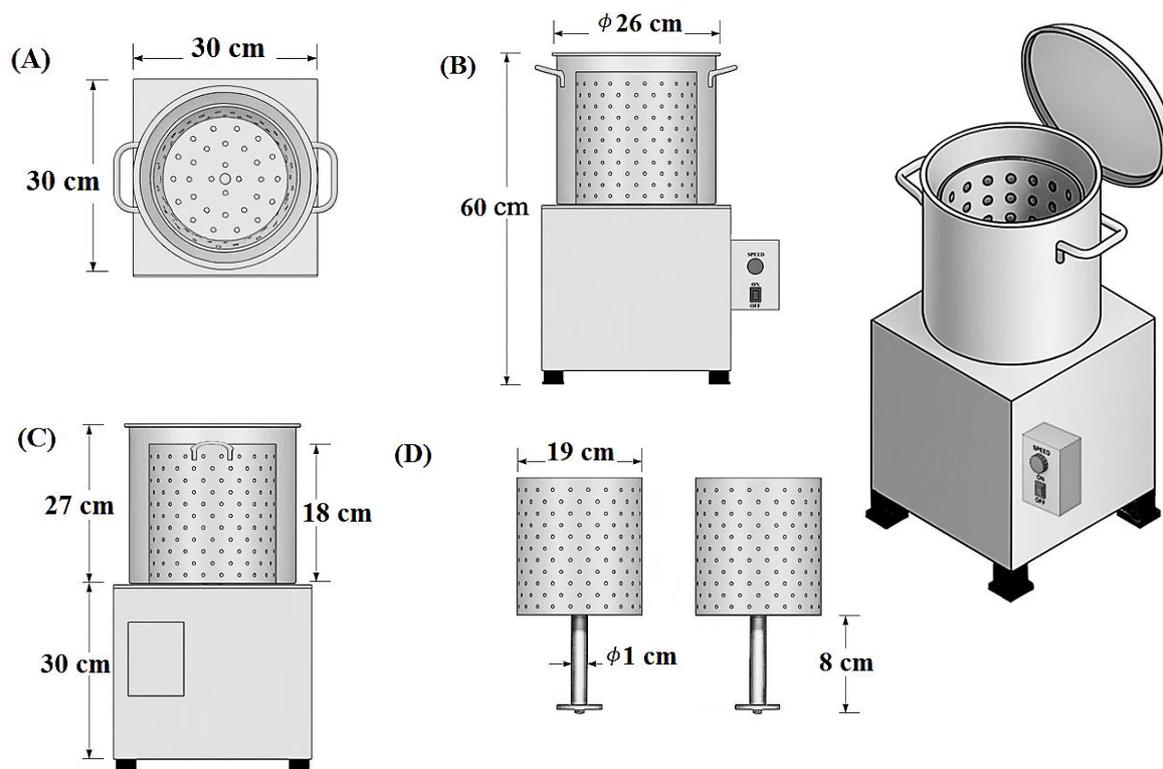
This study involved developing and constructing a vertical centrifugation-based de-oiling machine specifically designed for making crispy fried enoki mushrooms. The research was conducted at the Department of Food Engineering, Faculty of Food and Agricultural Technology, and the Department of Production Engineering Technology, Faculty of Industrial Technology, Pibulsongkram Rajabhat University in Phitsanulok, Thailand.

2.1 Design and development of a de-oiling machine with vertical centrifugation technique

The de-oiling machine adopted a vertical centrifugal technique to remove any remaining oil from fried food products such as crispy fried enoki mushrooms. This machine had a maximum capacity of 500 g and could operate at a de-oiling speed of 1,350 rpm. The machine was user-friendly and compatible with food components, allowing effortless removal and cleaning to prevent the accumulation of bacteria and food residue. The diagram of the machine is shown in Figure 1. The developed machine was designed to consist of a main frame, a material hopper and vertical centrifugal traps, and its specifications are shown in Table 1.

Table 1 The specifications of the de-oiling machine with vertical centrifugation technique.

Detail	Shape (cm)			Dimension (cm)	
	Length	Width	Height	Diameter	Height
Main frame	30	30	60		
Material hopper				26	27
Vertical centrifugal trap				19	18
Vertical centrifugal holes				0.5	
Vertical centrifugal shaft				1	8

**Figure 1** The diagram of the de-oiling machine with vertical centrifugation technique (A) top view, (B) front view, (C) right view, and (D) vertical centrifugation traps.

The de-oiling machine was operated using the vertical centrifugation technique, as shown in Figure 1 and Table 1. The primary frame of the machine had dimensions of 30 cm in length, 30 cm in width, and 60 cm in height. The material hopper had a diameter of 26 cm and a height of 27 cm. The vertical centrifugal trap had a diameter of 19 cm, a height of 18 cm, and holes with a diameter of 0.5 cm. The diameter of the vertical centrifugal shaft was 1 cm, while its height was 8 cm. The maximum capacity of the vertical centrifugal trap was 500 g, which was suitable for crispy fried enoki mushrooms or other raw materials. The vertical centrifugation process may be initiated at a speed of 1,350 rpm by starting the machine using the power control cabinet. The centrifugal speed can be adjusted to one of nine different levels. The enoki mushrooms, which have been made crispy, undergo centrifugation, resulting in the removal of oil through a pipe at the bottom of the machine.

2.2 Preparation of crispy fried enoki mushrooms

The enoki mushrooms used in this research were procured from Phlai Chumphon Subdistrict, Mueang District, Phitsanulok Province, Thailand. In this study, the mushrooms were chosen based on their freshness, white color, and absence of any dark spots. The base of the mushroom was dry, and mucus was absent. The enoki mushroom

cap should be firm, free from any signs of opening, and highly clustered. The trunk had an extended and thin morphology; alternatively, it was straight. Enoki mushrooms were packaged in a packaging that ensured perfect dryness and was devoid of water droplets. The initial step involved trimming the tips of the enoki mushrooms to around 3 cm in length, as shown in Figure 2(A). Subsequently, clean water was employed to rinse off any remaining dirt particles, and the mushrooms were then gently dried using a paper towel to remove any surplus water. Subsequently, 200 g of mushrooms were subjected to horizontal cutting and subsequently mixed with a mixture of crispy flour and water, with a ratio of 1.5 parts crispy flour to 1 part water. Meanwhile, the oil was heated in a deep fryer to a temperature of 180 °C. The mushrooms underwent a frying process for approximately 13 min, resulting in the appearance of a golden-yellow color commonly associated with fried products (Figure 2(B)). The appearance of this color on fried enoki mushroom surfaces is the result of the Maillard reaction [18-19], which is often used as an indicator of the doneness and quality of fried food products. This color change not only indicates readiness but also is associated with a desirable texture, aroma, and flavor in common fried foods [20]. The fried enoki mushrooms were subsequently transferred to the de-oiling machine for the removal process using the vertical centrifugation technique, as shown in Figure 2(C).

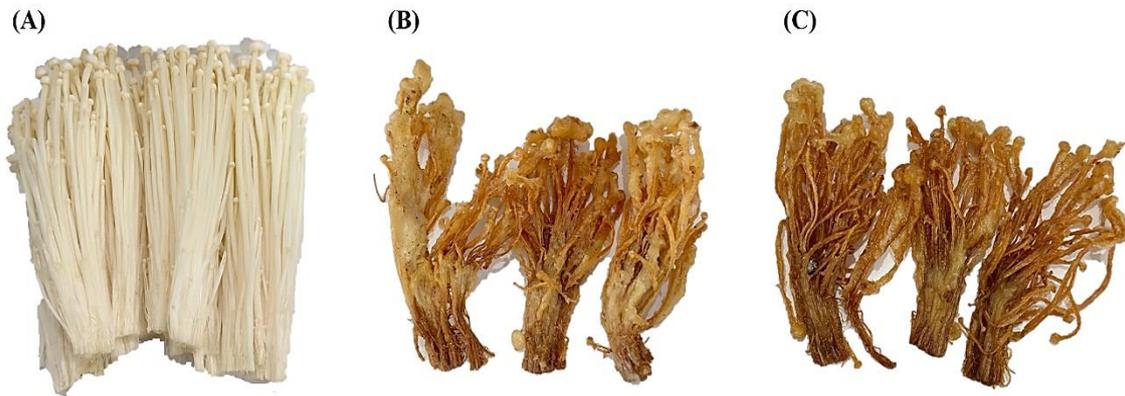


Figure 2 The crispy fried enoki mushrooms (A) fresh enoki mushrooms, (B) enoki mushrooms, and (C) de-oiled enoki mushrooms.

2.3 De-oiling experiments

After the crispy fried enoki mushrooms had been prepared, a fried sample was placed through a de-oiling machine utilizing a vertical centrifugal technique to remove any residual oil. The device was designed to operate at rotational rates of 1,350 rpm, with an option to adjust the speed to three different levels: 6, 7, and 8. Furthermore, the sample was examined using three different centrifugation durations: 30, 40, and 50 sec [16, 21]. The crispy fried enoki mushroom samples were weighed using a digital weighing scale (Mettler Toledo, Inc., model ME3002E, Switzerland) both before and after de-oiling.

2.4 Testing and Evaluation of the de-oiling machine of vertical centrifugation method

The investigation focused on determining the quantity of oil removed from the de-oiling machine using the vertical centrifugation technique. This was done by comparing the weight of each sample before and after the de-oiling process. Equation (1), adapted from Devi et al. [22], was utilized to calculate the yield of the crispy fried enoki mushroom samples following the de-oiling process. The de-oiling process efficiency of this equipment was determined using Equation (2).

$$W_y = \frac{W_{fde}}{W_{fa}} \times 100 \quad (1)$$

$$E_{do} = \frac{W_{fa} - W_{fde}}{W_{fa}} \times 100 \quad (2)$$

where

W_y = Weight yield (%)

W_{fde} = Weight of food after de-oiling (g)

W_{fa} = Weight of food after deep frying (g)

E_{do} = Efficiency of de-oiling (%)

2.5 Texture quality and water activity of crispy fried enoki mushrooms

The texture quality of the crispy fried enoki mushrooms after both the frying and de-oiling processes was investigated for hardness [23] using a texture analyzer (Brookfield AMETEK, Inc., model CT3, England) with a ball head operating at a test speed of 3 cm/min. All the samples were tested for water activity (a_w) using a water activity meter (METER Group, Inc., model AquaLab PRE, USA).

2.6 Chemical properties of crispy fried enoki mushroom

The chemical quality of the crispy fried enoki mushroom samples was investigated in terms of the fat content, according to the AOAC (2000) method.

2.7 Statistical analysis

This research involved three replications, and the results were analyzed and expressed as mean \pm standard deviation. The statistical analysis was performed using one-way analysis of variance (ANOVA) with a computer program at a confidence level of 95% ($p \leq 0.05$).

3. Results and Discussion

3.1 The effect of the development of the de-oiling machine of vertical centrifugation method

In this study, a de-oiling machine was designed using the vertical centrifugation technique for application with crispy fried enoki mushrooms, as shown in Figure 3. A sample of crispy fried enoki mushrooms was placed into the machine, and the power control was turned on, setting the centrifugal speed to 1,350 rpm. The efficiency of the machine was tested at three speed levels: 6, 7, and 8. Each level has different operating characteristics, including low speed, medium speed with higher centrifugal force, and maximum speed with the highest centrifugal force. Each speed level was investigated alongside three different durations of the de-oiling process: 30, 40, and 50 sec. During this process, the machine underwent centrifugation along the vertical axis, resulting in the removal of excess oils from the sample using a centrifugal sieve. The oil that came out was drained down into the bottom pipe of the machine to measure the quantity of oil removed.

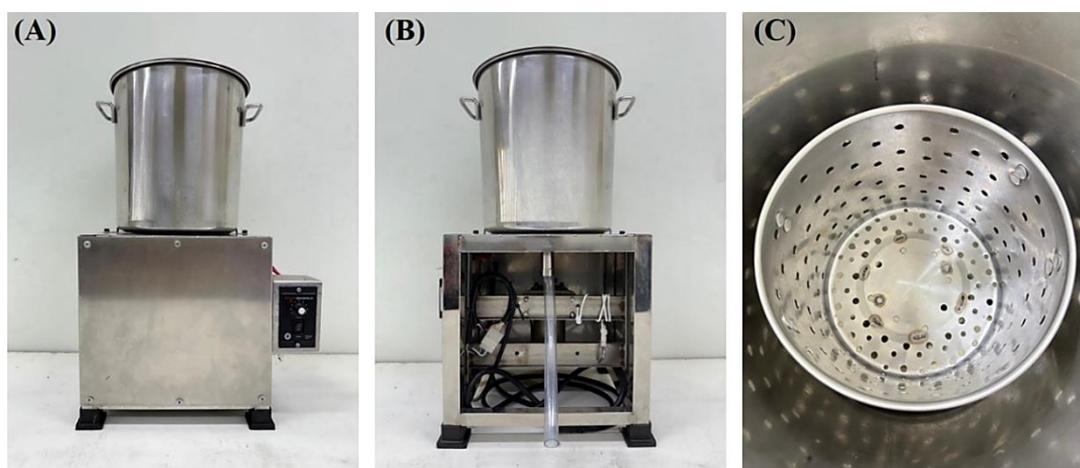


Figure 3 The de-oiling machine with vertical centrifugation technique (A) front view, (B) back view, and (C) top view.

3.2 The effect of evaluation of the de-oiling machine of vertical centrifugation method

This study evaluated the efficiency of the de-oiling machine using the vertical centrifugation technique, as shown in Table 2, as well as the texture quality, water activity, and chemical properties of crispy fried enoki mushrooms, as shown in Tables 3 and 4. Table 2 presents the yield and efficiency of the de-oiling machine utilizing the vertical centrifugation technique. The study revealed that the de-oiling speed level and duration had significant effects on the weight yield and de-oiling efficiency of the machine ($p < 0.05$) when operated at speed levels 7 and 8. There were no significant changes in the weight yield or de-oiling efficiency at these de-oiling durations for speed level 6 ($p > 0.05$). The highest weight yield and lowest de-oiling efficiency were observed at speed level 7 for a duration of 30 sec, with values of $97.12 \pm 0.30\%$ and $2.93 \pm 0.38\%$, respectively. This was followed by speed level 8 for a period of 40 sec. The most effective operational condition for the de-oiling process was found to be speed level 8 for a duration of 30 sec. This resulted in a weight yield of $91.59 \pm 0.70\%$ after de-oiling, along with an efficiency of $8.41 \pm 0.7\%$. This combination exhibited better de-oiling for the crispy fried enoki mushroom samples compared to the other conditions. However, an unexpected result was observed at speed level 7 for 30 sec, which produced the highest weight yield but the lowest de-oiling efficiency. This inverse relationship may be due to complex interactions between oil adhesion, sample structure, and possible variations in the sample moisture content or coating thickness. This inconsistency suggests that the rotational speed level and time did not fully explain the de-oiling efficiency.

Table 2 The efficiency of the de-oiling machine with vertical centrifugation technique with different de-oiling processes.

Speed level	Time (sec)	Mean \pm S.D. value			
		Weight of food after deep frying (g)	Weight of food after de-oiling (g)	Weight yield (%)	Efficiency of de-oiling (%)
6	30	141.23 \pm 0.37 ^f	136.48 \pm 0.45 ^f	96.64 \pm 0.37 ^{ab}	3.36 \pm 0.37 ^{cd}
	40	149.36 \pm 0.44 ^d	143.53 \pm 0.42 ^d	96.10 \pm 0.53 ^{ab}	3.90 \pm 0.53 ^{cd}
	50	154.31 \pm 1.22 ^a	148.31 \pm 0.42 ^a	96.11 \pm 0.79 ^{ab}	3.89 \pm 0.79 ^{cd}
7	30	151.17 \pm 0.58 ^{bc}	146.82 \pm 0.18 ^b	97.12 \pm 0.30 ^a	2.93 \pm 0.38 ^d
	40	153.69 \pm 0.27 ^a	144.88 \pm 1.04 ^c	94.27 \pm 0.68 ^c	5.73 \pm 0.68 ^b
	50	145.98 \pm 0.88 ^c	140.75 \pm 0.36 ^c	96.42 \pm 0.35 ^{ab}	3.58 \pm 0.35 ^{cd}
8	30	150.85 \pm 0.42 ^{bc}	138.17 \pm 0.68 ^g	91.59 \pm 0.70 ^d	8.41 \pm 0.70 ^a
	40	151.97 \pm 0.02 ^b	147.07 \pm 0.56 ^{ab}	96.78 \pm 0.36 ^a	3.22 \pm 0.36 ^d
	50	150.94 \pm 0.56 ^c	144.07 \pm 1.44 ^{cd}	95.45 \pm 1.37 ^b	4.55 \pm 1.37 ^c
Control		150.73 \pm 0.09 ^c	-	-	-

Note: a-g = different letters in the same column refer to a significant difference according to Duncan's New Multiple Range Test at the 95% confidence level ($p < 0.05$)

This study examined the hardness and water activity of the samples, as shown in Table 3. It was found that both the speed level and de-oiling time had statistically significant effects on the hardness and a_w of the products ($p < 0.05$). Under the working condition of speed 8 for 30 sec, the sample had the highest hardness at 30.60 ± 1.46 N, which was significantly different from the control sample ($p < 0.05$). In addition, the a_w value under this condition was also the lowest (0.32 ± 0.00), which was significantly different from the control sample ($p < 0.05$). The results showed that the fried enoki mushrooms de-oiled under this condition had more crispiness than the control sample, which was due to the efficient de-oiling. On the other hand, the control sample had a high residual oil content, resulting in a higher a_w value and lower hardness. For the samples de-oiled at speed level 6 for 40 sec, as well as speed level 7 at 30 and 40 sec, the hardness value was low and the a_w value was high, reflecting the less efficient oil removal. Therefore, these samples were less brittle and had more residual oil than the other groups.

However, an extended de-oiling time could damage crispy fried enoki mushroom samples. Nevertheless, the texture of fried food and the presence of residual oils in a product may be influenced by the use of flour and the frying process. According to research conducted by Bhuiyan and Ngadi [21], coating in flour and frying in oil were observed to affect the surface structure of food. The level of oil dispersion in the batter was mainly affected by the batter recipe and frying duration. Furthermore, Wang et al. [24] examined the potential impact of flour composition on the oil absorption and texture of fried nuts. Mixing starch and resistant proteins into the flour might effectively decrease the oil level, resulting in crispy fried nuts. Thus, the aim of this study was to investigate the efficacy with which a machine removed oil from crispy fried enoki mushroom samples, in addition to measuring their hardness. Furthermore, to enhance the crispiness of the food and meet the requirements of healthy consumers, it is necessary to use a suitable drying method for all the ingredients before the frying process. The food structure expands and increases in porosity, resulting in a crunchier texture and preventing oil absorption. Because of the quick oil migration into the food matrix; the quick cooling and solidification of the surface oil; and

the early hardness of the food surface, the de-oiling efficiency will diminish after frying. To enhance the de-oiling efficiency, the centrifugal process must be carried out as soon as possible after frying, when the oil is still hot and mostly on the surface [23-27].

Table 3 Hardness and water activity of crispy fried enoki mushroom after different de-oiling processes.

Speed level	Time (sec)	Mean \pm S.D. value	
		Hardness (N)	Water activity (a_w)
6	30	23.36 \pm 0.21 ^{de}	0.37 \pm 0.00 ^d
	40	21.13 \pm 1.12 ^{fg}	0.35 \pm 0.00 ^c
	50	25.17 \pm 1.04 ^{cd}	0.35 \pm 0.00 ^c
7	30	19.03 \pm 0.52 ^g	0.38 \pm 0.00 ^c
	40	20.79 \pm 2.56 ^{fg}	0.37 \pm 0.00 ^d
	50	22.08 \pm 1.22 ^{ef}	0.36 \pm 0.00 ^c
8	30	30.60 \pm 1.46 ^a	0.32 \pm 0.00 ^a
	40	27.12 \pm 0.99 ^{bc}	0.33 \pm 0.00 ^b
	50	29.91 \pm 1.70 ^a	0.33 \pm 0.00 ^b
Control		28.36 \pm 0.21 ^{ab}	0.37 \pm 0.00 ^d

Note: a-g = different letters in the same column refer to a significant difference according to Duncan's New Multiple Range Test at the 95% confidence level ($p < 0.05$)

Table 4 Fat content of crispy fried enoki mushroom after the different de-oiling process.

Speed level	Time (sec)	Mean \pm S.D. value
		Fat (%)
6	30	36.58 \pm 2.64 ^b
	40	38.73 \pm 0.53 ^{bc}
	50	36.95 \pm 0.30 ^b
7	30	44.00 \pm 0.48 ^d
	40	41.21 \pm 1.14 ^c
	50	38.92 \pm 2.73 ^{bc}
8	30	31.32 \pm 1.08 ^a
	40	33.04 \pm 0.55 ^a
	50	31.71 \pm 1.81 ^a
Control		45.05 \pm 0.28 ^d

Note: a-d = different letters in the same column refer to a significant difference according to Duncan's New Multiple Range Test at the 95% confidence level ($p < 0.05$)

Table 4 shows the fat content of the crispy fried enoki mushrooms after the de-oiling process under different conditions. The control sample had the highest fat content at 45.05 \pm 0.28%, which was significantly different from most samples ($p < 0.05$), except for the group de-oiled at speed level 7 for 30 sec, for which the fat content was 44.00 \pm 0.48%. Compared with the control group, the samples de-oiled at speed level 8 for 30, 40, and 50 sec had significantly reduced fat content, observed as 31.32 \pm 1.08%, 33.04 \pm 0.55% and 31.71 \pm 1.81%, respectively ($p < 0.05$). These three groups showed superior oil removal efficiency to that obtained under the other conditions. In addition, the reduced fat content was consistent with the weight loss data in Table 2, especially the speed level 8 condition for 30 sec, which resulted in a fat content reduction of more than 10% compared to the control sample, indicating the optimum suitability of this condition for reducing the oil content in the product.

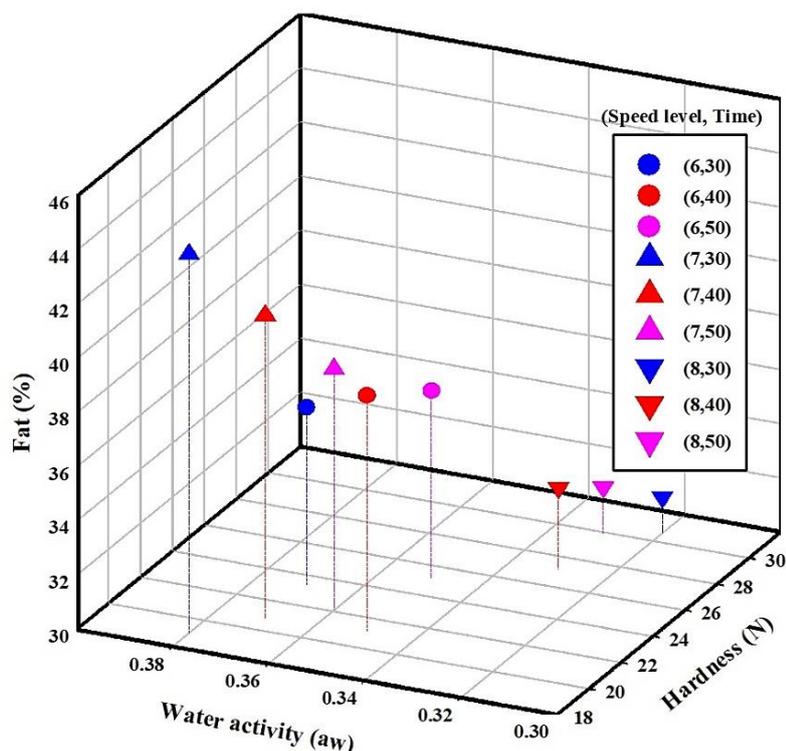


Figure 4 The relationship between hardness, water activity and fat content of crispy fried enoki mushroom after the different de-oiling processes.

Figure 4 shows the relationship between hardness, water activity, and fat content in crispy fried enoki mushrooms processed using different de-oiling processes. In general, the results show that as the a_w decreased, the hardness increased because lower moisture content leads to a firmer texture. During frying, water evaporates from the surface, causing the food to dry out and become harder, which is a characteristic typical of fried foods. However, Figure 4 also shows that this trend did not always follow a consistent pattern. In some cases, both the a_w and hardness decreased simultaneously, contradicting the expected outcome. This inconsistency suggests that factors beyond moisture loss may have influenced the hardness. For instance, rapid water evaporation can damage the internal microstructure of food, leading to structural collapse and a softer texture, even when the a_w is reduced. Fat absorption, structural changes, and the interaction between frying and de-oiling processes may also contribute to these variations. Overall, these observations suggest that the relationship between the a_w and hardness is not strictly linear; instead, it is influenced by the rate of moisture loss and structural transformations within the food matrix.

Additionally, fat content has a significant impact on texture. A higher fat content can create a softer texture since fat acts as a lubricant, reducing hardness. However, if fat solidifies on the surface, this may enhance crispiness rather than tenderness. Conversely, a lower fat content can lead to a firmer texture due to the lack of lubrication. The distribution of fat within food is crucial in determining its texture. When fat is evenly absorbed throughout the food, this can result in a softer texture. In contrast, fat that remains concentrated on the surface tends to enhance crispiness. This suggests that fat absorption does not always directly correlate with a softer texture [6, 28-33]. As shown in Figure 4, fat content does not exhibit a direct correlation with hardness, emphasizing the role of the de-oiling process in determining the final texture of fried foods. According to Table 4 and Figure 4, a centrifugation speed of level 8 resulted in the lowest fat content (31.32–33.04%) and the highest hardness, indicating that an efficient de-oiling process would effectively remove fat and increase hardness. In contrast, at speed level 7, the fat content remained relatively high compared to when speed level 8 was used, especially as the centrifugation time was extended. These outcomes may have been due to the use of insufficient centrifugal force to extract fat that had already penetrated the internal structure of the food, causing some fat to remain trapped and resistant to external separation. As a result, a higher fat content was retained, which contributed to the softer and less desirable texture. At speed level 6, the fat content was moderate but did not follow a consistent trend, leading to variations in hardness. Greater fat retention may result in a softer and less firm texture due to increased lubrication, whereas efficient fat removal contributes to a crisper texture. Among the tested conditions, centrifugation at speed level 8 for 30 sec proved the most effective in removing oil, reducing the weight loss to $8.41 \pm 0.72\%$, lowering the a_w to 0.32 ± 0.00 , and increasing the hardness to 30.60 ± 1.46 N. These conditions produced a noticeably crisper texture compared to those of the samples that had not been de-

oiled. The findings suggest that optimizing the de-oiling process at this speed and duration would contribute to achieving the desired crispiness by effectively balancing the fat removal and moisture content. This effect could be attributed to excessive fat absorption early in the process, which gradually reduces the efficiency of fat removal. Furthermore, the amount of oil separated during centrifugation (Figure 5) indicates that centrifugal force and oil viscosity interact in a manner that can limit the efficiency of oil separation under certain conditions; for example, if the oil viscosity is high, the centrifugal force may not be able to separate the oil from the food surface. Although de-oiling successfully removes oil and lowers a_w , its impact on fat reduction and food hardness depends on multiple factors. The relationship between a_w and hardness is complex, influenced by fat content, de-oiling efficiency, and frying conditions. These findings indicate that the de-oiling process developed in this study is a practical approach for producing crispy fried enoki mushrooms, making them a suitable option for health-conscious consumers. While a decrease in a_w is generally associated with increased hardness, other factors such as fat absorption, de-oiling efficiency, and frying conditions also contribute. The fat content can either soften or firm the texture depending on how it is distributed within the food structure [32-33]. Therefore, achieving the right balance between moisture loss and fat absorption is key to determining the final texture of crispy fried enoki mushrooms.



Figure 5 Effect of centrifugation duration for de-oiling process on crispy fried enoki mushroom.

4. Conclusions

This study focused on the development and performance evaluation of a de-oiling machine that used vertical centrifugation and was specifically designed to reduce the fat content in crispy fried enoki mushrooms. The machine was tested at speed levels 6, 7, and 8 for durations of 30, 40, and 50 sec to determine the most effective de-oiling condition. The results indicated that the optimal condition was speed level 8 for 30 sec, which resulted in a weight loss of $8.41 \pm 0.72\%$, reduced the water activity to 0.32 ± 0.00 , and achieved a hardness of 30.60 ± 1.46 N. These characteristics led to a crisper texture compared to the untreated sample. The developed de-oiling machine successfully reduced the fat content in fried enoki mushrooms while preserving their desirable sensory qualities, meeting the preferences of health-conscious consumers. This approach provides a promising alternative for improving the nutritional profile of fried foods without compromising their taste or texture. Further improvements are suggested, such as pre-drying mushrooms before frying to minimize the oil absorption and applying starch coatings to enhance the crispiness and further reduce the fat uptake.

Future research should also involve more accurate methods for assessing color changes using instrumental techniques and maintaining precise temperature control during frying to improve consistency. Additionally, investigating the relationship between microstructural changes and key quality factors such as water activity, hardness, and fat content would deepen understanding of textural development and support the creation of healthier fried food products that meet the demands of modern consumers.

5. Acknowledgements

The authors would like to thank Pibulsongkram Rajabhat University, the Department of Food Engineering, and the Faculty of Agricultural and Food Technology for the place, experiment, and equipment for the research. In addition, the authors would like to thank the Department of Production Engineering Technology, Faculty of Industrial Technology, for providing the facilities for this research.

6. References

- [1] Wunjuntuk K, Ahmad M, Techakriengkrai T, Chunhom R, Jaraspermsuk E, Chaisri A, et al. Proximate composition, dietary fibre, beta-glucan content, and inhibition of key enzymes linked to diabetes and obesity in cultivated and wild mushrooms. *J Food Compos Anal.* 2022; 105:104-226.
- [2] Ikeda S, Yamauchi M, Watari T, Hatamoto M, Yamada M, Maki S, et al. Development of enokitake (*Flammulina velutipes*) mushroom cultivation technology using spent mushroom substrate anaerobic digestion residue. *Environ Technol Innov.* 2021; 24:1020-1046.
- [3] Fukushima M, Ohashi T, Fujiwara Y, Sonoyama K, Nakano M. Cholesterol-lowering effects of maitake (*Grifola frondosa*) fiber, shiitake (*Lentinus edodes*) fiber, and enokitake (*Flammulina velutipes*) fiber in rats. *Exp Biol Med.* 2001;226(8):758–765.
- [4] Yeh MY, Ko WC, Lin LY. Hypolipidemic and antioxidant activity of enoki mushrooms (*Flammulina velutipes*). *Biomed Res Int.* 2014;2014(1):352-385.
- [5] Navarro-Simarro P, Gómez-Gómez L, Ahrazem O, Rubio-Moraga Á. Food and human health applications of edible mushroom by-products. *New Biotechnol.* 2024; 81:43–56.
- [6] Liu Y, Tian J, Zhang T, Fan L. Effects of frying temperature and pore profile on the oil absorption behavior of fried potato chips. *Food Chem.* 2021; 345:128832.
- [7] Yang D, Wu G, Li P, Zhang H, Qi X. Comparative analysis of the oil absorption behavior and microstructural changes of fresh and pre-frozen potato strips during frying via MRI, SEM, and XRD. *Food Res Int.* 2019; 122:295–302.
- [8] Durán M, Pedreschi F, Moyano P, Troncoso E. Oil partition in pre-treated potato slices during frying and cooling. *J Food Eng.* 2007;81(1):257–265.
- [9] Blumenthal MM, Stier RF. Optimization of deep-fat frying operations. *Trends Food Sci Technol.* 1991; 2:144–148.
- [10] Patil RS, Waghmare J, Annapure U. Comparative assessment of the frying performance of palm olein and sunflower oil during deep-fat frying of Indian battered food products. *J Agric Food Res.* 2023; 14:1007-1078.
- [11] Choe E, Min DB. Chemistry of deep-fat frying oils. *J Food Sci.* 2007;72(5): R77–86.
- [12] Al Faruq A, Khatun MHA, Azam SR, Sarker MSH, Mahomud MS, Jin X. Recent advances in frying processes for plant-based foods. *Food Chem Adv.* 2022; 1:100-186.
- [13] Van Vliet T, Visser JE, Luyten H. On the mechanism by which oil uptake decreases crispy/crunchy behaviour of fried products. *Food Res Int.* 2007;40(9):1122–1128.
- [14] Da Silva PF, Moreira RG. Vacuum frying of high-quality fruit and vegetable-based snacks. *LWT-Food Sci Technol.* 2008;41(10):1758–1767.
- [15] Dehghannya J, Ngadi M. Recent advances in microstructure characterization of fried foods: Different frying techniques and process modeling. *Trends Food Sci Technol.* 2021; 116:786–801.
- [16] Moreira RG, Da Silva PF, Gomes C. The effect of a de-oiling mechanism on the production of high-quality vacuum fried potato chips. *J Food Eng.* 2009;92(3):297–304.
- [17] Kim T, Moreira RG. De-oiling and pretreatment for high-quality potato chips. *J Food Process Eng.* 2013;36(3):267–275.
- [18] Pedreschi F, Kaack K, Granby K. Colour changes and acrylamide formation in fried potato slices. *LWT-Food Sci Technol.* 2005;38(5):499–506.
- [19] Bordin K, Kunitake MT, Aracava KK, Trindade MA. Changes in food caused by deep fat frying – A review. *Arch Latinoam Nutr.* 2013;63(1):90–98.
- [20] Dangal S, Thapa S, Thapa S, Shrestha AK. Review on deep-fat fried foods: chemical and physical changes, health implications, and mitigation strategies. *Eur Food Res Technol.* 2024;250(1):11–29.
- [21] Bhuiyan MHR, Ngadi M. Post-fry oil distribution in batter coated fried foods. *LWT.* 2024; 194:115819.
- [22] Devi S, Zhang M, Ju R, Mujumdar AS. Co-influence of ultrasound and microwave in vacuum frying on the frying kinetics and nutrient retention properties of mushroom chips. *Dry Technol.* 2019;38(15):2102–2111.
- [23] Pedreschi F, Leon J, Mery D, Moyano P, Pedreschi R, Kaack K, et al. Colour development and acrylamide content of pre-dried potato chips. *J Food Eng.* 2007;79(3):786–793.
- [24] Wang QL, Yang Q, Kong XP, Chen HQ. The addition of resistant starch and protein to the batter reduces oil uptake and improves the quality of the fried batter-coated nuts. *Food Chem.* 2024; 438:137992.

- [25] Liu Y, Tian J, Hu B, Yu P, Fan L. Relationship between crust characteristics and oil uptake of potato strips with hot-air pre-drying during frying process. *Food Chem.* 2021; 360:130-145.
- [26] Omidiran AT, Odukoya OJ, Akinbule OO, Sobukola OP. Effect of microwave-assisted pre-drying and deep-fat-frying conditions on some quality attributes of orange fleshed sweetpotato chips. *Food Chem Adv.* 2023; 3:1005-1034.
- [27] Cruz G, Cruz-Tirado JP, Delgado K, Guzman Y, Castro F, Rojas ML, et al. Impact of pre-drying and frying time on physical properties and sensorial acceptability of fried potato chips. *J Food Sci Technol.* 2018; 55:138–144.
- [28] Gomide AI, Monteiro RL, Laurindo JB. Impact of the power density on the physical properties, starch structure, and acceptability of oil-free potato chips dehydrated by microwave vacuum drying. *LWT.* 2022; 155:112917.
- [29] Vitrac O, Trystram G, Raoult-Wack AL. Deep-fat frying of food: Heat and mass transfer, transformations and reactions inside the frying material. *Eur J Lipid Sci Technol.* 2000;102(8–9):529–538.
- [30] Achir N, Kara W, Chipeaux C, Trezzani I, Cuvelier ME. Effect of energy transfer conditions on the chemical degradation of frying oil. *Eur J Lipid Sci Technol.* 2006;108(12):999–1006.
- [31] Ziaifar AM, Achir N, Courtois F, Trezzani I, Trystram G. Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process. *Int J Food Sci Technol.* 2008;43(8):1410–1423.
- [32] Lin H-TV, Hou P-H, Sung W-C. Kinetics of oil absorption and moisture loss during deep-frying of pork skin with different thickness. *Foods.* 2021; 10:3029.
- [33] Mahmud N, Islam J, Oyom K, Adrah K, Adegoke SC, Tahergorabi R. A review of different frying oils and oleogels as alternative frying media for fat-uptake reduction in deep-fat fried foods. *Heliyon.* 2023;9(11): e21500.