Current Applied Science and Technology e-ISSN: 2586-9396

Curr. Appl. Sci. Technol. ….., Vol... (No...), e0264433

Research article

Influence of Pre-treatment Techniques on Quality of Vacuum-Fried Carrot Chips

Puletipalli Babu[1], Deepanka Saikia[2]*, Rajesh G K[3], Prakash Kumar Nayak[4], Sudheer K P[3] and Jinukala Srinivas[2]

[1]*Krishi Vigyan Kendra, Acharya N. G. Ranga Agricultural University, Kondempudi, Andhra Pradesh, India*
[2]*Department of Agricultural Engineering, Centurion University of Technology and Management, Paralakhemundi, Odisha, India*
[3]*Department of Processing and Food Engineering, KCAET, KAU, Tavanur, Kerala, India*
[4]*Department of Food Engineering and Technology, Central Institute of Technology, Kokrajhar, Assam, India*

Received: 18 August 2024, Revised: 17 March 2025, Accepted: 17 March 2025, Published: 18 August 2025

Abstract

The influence of various pre-treatments on the physicochemical properties of vacuum-fried (VF) carrot chips, including blanching (85°C for 3.5 min), blanching combined with drying (85°C for 3.5 min followed by drying at 70°C for 1 h 30 min), blanching combined with freezing (85°C for 3.5 min followed by freezing at -20°C for 4 to 5 h), freezing (-18°C overnight), and edible gum coating (dipping in 1.5% guar gum for 5 min), was compared with untreated (control) and atmospheric-fried carrot chips. The processing conditions, such as frying temperature (100°C), frying pressure (9 kPa), and frying time (20 min), were selected for the pre-treatment study. Refined palm oil was used for vacuum frying, and de-oiling was carried out at 1000 rpm for 10 min. Quality parameters such as oil content, moisture content, water activity, total yield, color, and sensory value were determined using standard procedures. The results revealed that the lowest moisture content (2.15%) and water activity (0.214) were observed in vacuum-fried carrot chips that underwent the blanching combined with drying pre-treatment. The lowest oil content (10.04%) was recorded in vacuum-fried edible gum-coated chips. Frozen pre-treated vacuum-fried carrot chips had the lowest hardness value of 1.282 N, and the maximum colour values were L* (38.92), a* (22.85), and b* (27.86). Based on the quality parameters and sensory evaluation of the vacuum-fried carrot chips, the freezing pre-treatment was found to be superior among the pre-treatments.

Keywords: pre-treatments; blanching; drying; vacuum frying; oil content; moisture content; sensory evaluation; carrot chips

*Corresponding author: E-mail: deepankasaikia@gmail.com
https://doi.org/10.55003/cast.2025.264433

1. Introduction

Carrots are highly nutritious vegetables consumed raw and in processed forms worldwide. They are rich in carotene, vitamins, pectin, dietary fibers, and essential minerals, making them a vital part of a healthy diet. In India, carrot cultivation is region-specific, with certain varieties adapted for particular climates and terrains. Among them, Ooty-1 is a prominent variety suitable for cultivation in hilly regions. This cool-season crop develops optimal color and quality when grown at temperatures between 15°C to 20°C, thriving in deep, loose loamy soils with a pH range of 6.0 to 7.0. Ooty-1 can be cultivated year-round at elevations above 1500 m with assured irrigation or during the July-February season at lower elevations. Known for its high yield potential (25-30 tons per hectare within 100-120 days) and resilience to pests, this variety ensures consistent quality, making it an excellent choice for processing into value-added products. The consumption of carrots and their value-added products has increased steadily due to the recognition of their antioxidant and anticancer activities (Ikram et al., 2024). However, fresh carrots are highly perishable and start spoiling within a day after harvest. The post-harvest losses of fresh products, including carrots, range from 14% due to their highly perishable nature, leading to challenges in distributing and marketing them (Yeshiwas & Tadele, 2021). The value addition of carrots is one of the most important technologies to reduce post-harvest losses and overcome these problems. Nowadays, there is an increasing demand for healthy snacks that provide nutritious foods to reduce obesity.

In the present era of junk foods, fried foods are gaining significant market importance. The snack food market has witnessed enormous growth within the food processing sector in India. This growth reflects the increasing consumer demand for convenient and enjoyable snack options. Crispy and crunchy snacks produced using frying, freezing, drying, and other processing methods enhance the acceptability and consumption of vegetables like carrots. Carrot chips, in particular, stand out as a popular snack due to their unique sensory attributes, being both dry and crispy.

Despite their potential, there is currently limited availability of ready-to-eat carrot chips in the market. However, these products have the advantage of a longer shelf life, making them an attractive option for commercial production (Chen et al., 2018).

Frying is a simple and commonly used method for cooking various foods, such as chips, french fries, meat, fruits, and vegetables. It involves immersing raw or pre-treated food items in hot oil at high temperatures (120-200°C) for a short duration (Al Faruq et al., 2022). Despite its popularity, a significant disadvantage of consuming deep-fried food is the high oil content, which is associated with several health issues, including cardiovascular diseases, diabetes, cancer, obesity, and hypertension (Bouchon & Dueik, 2018; Mesias et al., 2021; Al Faruq et al., 2022). Given these concerns, there is a growing demand for healthy yet tasty snack products with reduced oil content. In this context, research has been focused on advanced processing technologies to produce high-quality fried products with lower oil content, free of acrylamide, and aligned with modern health trends.

The technology of vacuum frying is the best option for the production of novel snacks that fulfil consumer demand and meet nutritional requirements (Dueik et al., 2010). The vacuum frying process is carried out in a closed system, and the samples are fried under vacuum conditions below atmospheric pressure (below 100 kPa). Due to the low pressure, the boiling point of the oil and water in the food is reduced (Ren et al., 2022). At such reduced pressures, the boiling point as well as the smoke point of oil is reduced. The absence of air during the frying process inhibits oxidation, including lipid oxidation and enzymatic browning, and thus retains color and flavor. Vacuum frying offers minimal changes in oil quality and desired organoleptic properties without loss in nutritional value. It is widely used for processing various foods, mostly vegetables and fruits. Vacuum frying offers improvements in the quality attributes of fried foods compared to atmospheric frying (Saikia et al., 2022). It maintains the color and flavor of the product. Moreover, the oil used in vacuum frying can be reused several times without affecting its quality, thus increasing economic feasibility of the process.

Some scientists mainly focus on preserving nutrients, retaining color and flavor, and reducing oil content during the vacuum frying process. In fact, some quality changes could take place during the vacuum frying process. To improve the quality of vacuum-fried products, several pre-treatment methods including blanching, blanching combined with drying, blanching combined with freezing, freezing, and edible gum coating (1.5%w/v) have been applied. Blanching is one of the most important pre-treatment methods used to prevent browning and remove water-soluble sugars from the food surface (Saini et al., 2023). To improve the product quality of fried food, blanching can produce considerable improvement in the color of the vacuum-treated samples and can reduce oil absorption. Blanching combined with drying is the best method to reduce the moisture content and water activity in chips. This may be due to the removal of moisture from the fried product during drying. Freezing is one of the popular and oldest methods of food preservation, which allows retention of the texture, taste, and nutritional values of foods. Gouyo et al. (2021) stated that during frying of frozen treated samples, free water between the cells tended to vaporize, and the interspaces left by water evaporation expanded, resulting in an increase in porosity and reduction in hardness. The main aim of gum coating is to reduce oil absorption in fried products. Reducing the fat content of fried foods by applying coatings is an alternative solution to comply with both health concerns and consumer preferences (Salehi et al., 2021). Hydrocolloids can also be used as coating material for fried food products to reduce oil absorption (Santos et al., 2023).

Fried snack foods are increasingly popular, yet traditional frying methods present significant health concerns due to the high oil content, which is linked to obesity, cardiovascular diseases, and diabetes. Additionally, despite their potential as a nutritious and shelf-stable snack, ready-to-eat carrot chips are limited in the market. This underscores the need for innovative frying technologies that can produce high-quality snacks with reduced oil content while retaining their nutritional and sensory qualities.

Vacuum frying has emerged as a promising solution to address these challenges. It offers reduced oil uptake and improved product quality and has been widely applied to various fruits, vegetables, cereals, and meat products. However, there is currently no literature available on the vacuum frying of carrot chips, specifically focusing on the Ooty-1 variety, which is commonly cultivated in India. Moreover, the effects of various pre-treatments on the physicochemical properties of vacuum-fried carrot chips remain unexplored, highlighting a significant gap in existing research.

Therefore, this research aimed to evaluate the effect of various pre-treatments on the physicochemical properties of vacuum-fried (VF) carrot chips, such as moisture content, oil content, water activity, texture, color, and sensory attributes, and to identify the most effective pre-treatment method for enhancing quality attributes like reduced oil uptake, improved texture, and superior sensory characteristics, thus meeting consumer demand for healthier and more nutritious snack options.

2. Materials and Methods

2.1 Collection of raw materials

The carrots used in this study were procured from the local market in Tavanur, Kerala, during November, 2023. The selected carrots were of the Ooty-1 cultivar, commonly grown in South India. These carrots were of medium-long size, with an average length of 20-30 cm and a diameter of 5-6 cm, which aligns with the maturity index for optimal processing. Carrots with visible defects such as damage, disease, or irregularities were excluded to maintain uniformity in processing.

The harvested carrots were packed in polythene bags and stored at a temperature of 0°C and a relative humidity of 95-100% (Camelo, 2004) to preserve their freshness and prevent deterioration until they were processed. The time between procurement and processing was kept within 24 h to minimize any loss of quality or nutritional value. The time between cutting and pre-treatment was limited to a maximum of 30 min to prevent oxidation and ensure optimal product quality. Refined palm oil (RPO), purchased from M/s. Fathima Stores in Tavanur, Kerala, was used as the frying medium for vacuum frying in this study.

2.2 Preparation of sample for vacuum frying

Carrots were manually cleaned, peeled using a hand peeler, and cut into fingers (even strips) using a vegetable dicer. The average thickness and diameter of the fingers were less than 3-4 mm and 6-7 mm, respectively. The sliced carrot was subjected to different pre-treatments, namely: blanching (85°C for 3.5 min, CB), blanching combined with drying (85°C for 3.5 min followed by drying at 70°C for 1 h 30 min, CBD), blanching combined with freezing (85°C for 3.5 min followed by freezing at -20°C for 4 to 5 h, CBF), freezing (-18°C overnight, CF), and edible gum coating (dipping in 1.5% guar gum for 5 min, CGG). The freezing conditions were designed to evaluate the impact of freezing rates on the quality parameters of VF-carrot chips. Slow freezing was achieved through overnight freezing at -18°C, while rapid freezing was conducted at -20°C for 4 to 5 h. These pre-treatment conditions were selected based on their potential to enhance the physicochemical properties of the final product. CB was employed to inactivate enzymes responsible for browning and reduce oil uptake by removing water-soluble sugars through blanching (Saini et al., 2023). CBD was aimed at lowering moisture content and water activity, and improving texture and shelf life (Fan et al., 2006). CBF retained color and enhanced porosity for a crispier product. CF preserved texture and nutritional quality while increasing porosity during frying (Gouyo et al., 2021). CGG formed a protective barrier, significantly reducing oil absorption and aligning with the demand for healthier snack options (Salehi et al., 2021). These five pre-treatments (CB, CBD, CBF, CF, and CGG) were compared with untreated fried samples (control, CC) and atmospheric fried samples (100°C for 20 min, CAF).

2.3 Vacuum frying procedure

Based on the previous study by Praveena et al., 2024, the combination of frying temperature (100°C), frying pressure (9 kPa), and frying time (20 min) was selected for the pre-treatment study of vacuum-frying carrot chips. The pre-treatments were chosen to reduce the oil uptake by the product during frying and to improve the quality characteristics of the fried product. Three kilograms of pre-treated carrot slices were fried in refined palm oil using the specified operational conditions. For centrifugation, the de-oiling motor rpm was set to a maximum of 1000 rpm for 10 min. The removal of surface oil from the fried carrot chips was achieved through the de-oiling process.

2.4 Determination of quality attributes of fried samples

2.4.1 Moisture content

The initial moisture content of the carrot slices was found to be 87% (dry basis). The moisture content of the pre-treated VF-carrot samples was determined using an infrared moisture analyzer (MA 160, Sartorius, Germany), as recommended by Saikia et al. (2022). Initially, a disposable aluminum pan was loaded into the moisture analyzer for calibration. After calibration was completed, 5 g of ground carrot chips were transferred into the aluminum pan, and the hood was closed for the moisture analyzer to run the test at 105°C. Upon completion of the test, which took 5-10 min, the moisture analyzer stopped automatically and displayed the percentage of moisture content of the tested sample. Subsequently, the moisture content was also evaluated using the oven-drying method recommended by AOAC (2019).

2.4.2 Oil uptake

The VF-carrot samples were ground and oven-dried for fat content analysis. The fat content of the VF-carrot chips was determined using a Soxhlet extractor (Extraction System, B-811, Buchi, India) with diethyl ether at 65°C for 5 h. On a dry basis, the fat content was determined as grams of fat per gram of dry solids (Manjunatha et al., 2014). The experiment was conducted in triplicate to ensure accuracy and reliability. The percentage of fat was determined using equation (1).

$$Fat\ Content\ (\%) = \frac{Wt.of\ fat\ recovered\ (g)}{Wt.of\ sample\ (g)} \times 100 \tag{1}$$

2.4.3 Water activity

The water activity of the pre-treated VF-carrot chips was determined using a water activity meter (M/s. AquaLab, Decagon Devices Inc., Pullman, WA, USA). This assessment plays a critical role in evaluating the moisture content and stability of the carrot chips during the vacuum frying process.

2.4.4 Texture

A texture analyzer (TA. XT Texture Analyzer, M/s. Stable Micro Systems Ltd.) was utilized to measure the breaking/penetration force of the food products, which was expressed in terms of Newtons (N) or grams (g). The hardness of the fried products was determined using the texture analyzer. During the testing process, a cylindrical/steel ball probe (P/0.25s), moving at a speed of 5 mm/s over a distance of 5.0 mm, was employed to break the chips (Yan et al., 2013). Once the probe made contact with the sample, the maximum force required to rupture the chips was observed and compared between the samples. The test was performed in triplicate.

2.4.5 Color

The color of the VF-carrot chips was determined using a Hunter Lab Colorimeter – ColorFlex EZ diffuse model. It operates on the principle of light focusing on the sample and measures reflected energy from the sample across the entire visible spectrum. The colorimeter has standard observer curves for red, green, and blue colors. This colorimeter expresses the colors using L*, a*, and b* values. The L* value represents lightness, ranging from 0 (blackness) to 100 (whiteness), where a* represents positive values for redness and negative values for greenness, while b* represents positive values for yellowness and negative values for blueness (Pathare et al., 2013). The color of the VF-carrot chips was measured using the CIELAB scale at a 10° observer angle with D65 illuminant and a 50 mm diameter measuring space. The sample was placed in a glass jar and filled up to the mark. The filled glass jar was then placed on the CIELAB scale. The deviation in color of the samples from the standard was observed and noted in triplicates. The total color change (ΔE) was determined based on equation (2) (Kurian et al., 2021).

$$\Delta E = \sqrt{\left(L_r - L_f\right)^2 + \left(a_r - a_f\right)^2 + \left(b_r - b_f\right)^2} \quad (2)$$

Where,

Lr, ar, br = values of L*, a*, b* before frying, and
Lf, af, bf = values of L*, a*, b* after frying.

2.4.6 Sensory analysis

The sensory analysis is the most important step for accepting or rejecting products by consumers. The sensory analysis of the product was evaluated using food quality attributes such as texture, color, flavor, taste, and overall acceptability (Ruiz-Capillas & Herrero, 2021). For sensory evaluation, a nine-point hedonic scale was used, and a scorecard was provided to highlight the good characteristics of pre-treated VF-carrot chips. The sensory evaluation of VF-carrot chips was conducted by a panel of 15 judges. The sensory evaluation protocol was approved by the institutional review board of Kelappaji College of Agricultural Engineering and Technology, Kerala Agricultural University, and all participants provided informed consent before the evaluation.

2.4.7 Statistical analysis

The data obtained from the experiments were statistically analyzed using IBM-SPSS Statistics 26.0. Measurements were performed in triplicate (n = 3) for each pre-treatment condition, with moisture content values measured across three separate trials to ensure reliability and account for variability. Analysis of variance (ANOVA) was performed to determine significant differences among the pre-treatment methods. A significance level of $\alpha = 0.05$ was set to assess the statistical significance of the results. Post-hoc comparisons were conducted using the Tukey HSD test to analyze differences between treatment groups.

3. Results and Discussion

The changes in the quality parameters of VF-carrot chips provided with different pre-treatments were compared with untreated and atmospheric fried samples.

3.1 Moisture content of VF-carrot chips

Moisture content is a crucial parameter that indicates the stability of the product during storage and represents the total amount of moisture present in the food. The moisture content of the vacuum-fried (VF) carrot chips is shown graphically in Figure 1. Moisture content values (n = 3) for each pre-treatment were recorded and analyzed. The data presented represent the mean of three trials, with standard deviations (SD) calculated to assess variability.

The pre-treatments had a significant ($p < 0.05$) effect on the moisture content of VF-carrot chips. As depicted in Figure 1, the moisture content ranged from 2.15% to 10.25%. The moisture contents for pre-treated VF-carrot chips were as follows: CB (3.59%), CBD (2.15%), CBF (2.93%), CF (2.67%), CGG (6.82%), CC (3.27%), and CAF (10.25%). The highest moisture content (10.25%) was observed in CAF, followed by CGG (6.82%). The high moisture content in CAF may be due to higher frying temperature, which resulted in minimal moisture removal and potential charring of the product (Maity et al., 2014). For the CGG pre-treatment, the higher moisture content could be attributed to the water-binding capacity of the guar gum used for coating, which formed a barrier around the carrot slices, limiting water evaporation during the pre-treatment process. Conversely, the lowest moisture content (2.15%) was found in VF-carrot chips pre-treated with CBD, which was likely due to moisture removal during the drying step. A similar trend was observed in VF-banana chips that underwent pre-treatment before frying (Udomkun & Innawong, 2018).

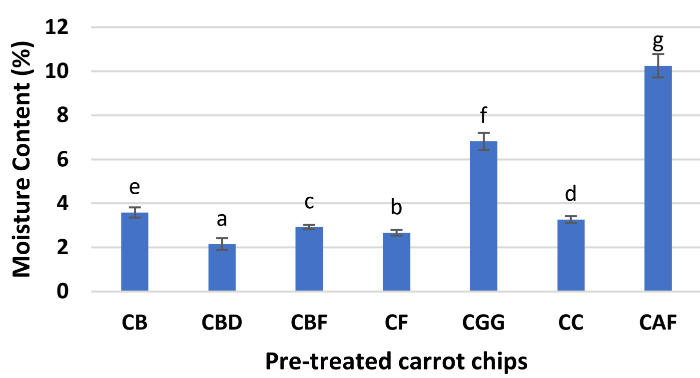

Figure 1. Effect of different pre-treatments on moisture content of VF-carrot chips. Moisture content (%) is presented with error bars representing standard deviations. Statistically significant differences between treatments are denoted by different letters (a, b, c, d, e, f and g), as determined by Tukey HSD post-hoc analysis ($p < 0.05$ for groups sharing the same letter); (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying).

3.2 Oil content of VF-carrot chips

The oil content is one of the most important parameters in snack foods. A lower oil content in food helps reduce health risks associated with diseases. The oil content of pre-treated (vacuum-fried) VF carrot chips is depicted in Figure 2. The oil content of the VF-carrot chips varied significantly ($p < 0.05$) with the pre-treatments. From Figure 2, it is evident that the oil content of pre-treated VF-carrot chips ranged between 10.04% and 30.05%. The maximum oil content of 30.05% was observed in the CAF, followed by the CC (25.11%), and CF (14.48%) pre-treated VF-carrot chips. The high oil absorption in CAF chips is not conducive to human consumption and is considered unsafe. The maximum oil absorption in CAF chips might be due to the high frying temperature and frying time. The oil content in the VF-chips was lower than that in CAF chips (Figure 2). The reason for the higher oil absorption in CF pre-treated chips might be due to an increase in porosity caused by the evaporation of ice crystals during frying (Fan et al., 2006). The obtained results were consistent with Ranasalva and Sudheer (2017), who observed a similar trend of oil absorption in frozen pre-treated VF-banana chips. The lowest oil content of 10.04% was noted in the VF-carrot chips pre-treated with CGG. This reduction in oil absorption may be due to the coating of carrot slices (1.5% w/v) with guar gum, which significantly reduced oil absorption. Yu et al. (2016) reported a similar trend of oil reduction (51.80%) in guar gum-coated VF-potato chips. The oil content of the VF-carrot chips pre-treated with CB, CBD, and CBF was 13.24%, 12.64%, and 13.98%, respectively. The oil content of VF-carrot chips was notably lower than many commercially available fried snack products. For instance, conventional deep-fat fried potato chips typically exhibit oil contents of 35% to 40%, primarily due to the higher frying temperature and extended frying times (Pedreschi, 2012). Similarly, atmospheric-fried banana chips were reported to have oil contents ranging from 30% to 38% (Ranasalva & Sudheer, 2017). By contrast, vacuum-fried fruit chips such as pineapple and shiitake mushroom chips had oil contents in the range of 18-25% under optimized conditions (Perez-Tinoco et al., 2008; Ren et al., 2018). Vacuum frying reduces oil absorption due to lower frying temperatures and the use of a de-oiling process, unlike atmospheric frying. The basic mechanism of oil absorption in the chips, or the amount of moisture loss from the chips, was directly proportional to the amount of oil entering into the chips (Liu et al., 2021). A higher frying temperature during the atmospheric frying process resulted in the scorching of samples, more oil absorption, and negligible moisture removal from them.

3.3 Water activity of VF-carrot chips

Water activity (a_w) plays a vital role in food, facilitating its safety and stability concerning the growth of microorganisms and chemical reactions. The water activity of VF-carrot chips varied significantly ($p < 0.05$) with the pre-treatments. The water activity of pre-treated VF-carrot chips is graphically represented in Figure 3. Water activity of the pre-treated VF-carrot chips ranged between 0.214 to 0.324, which was well below the threshold limit of 0.6. Water activity levels below 0.6 are considered safe for storage as they inhibit the growth of most bacteria, yeasts, and molds (Tapia et al., 2020). The water activity of the pre-treated VF-carrot chips, namely CB, CBD, CBF, CF, and CGG, were 0.316, 0.214, 0.292, 0.225, and 0.324, respectively. A water activity of 0.287 and 0.310 was observed in the CC chips and CAF chips, respectively. The highest water activity of 0.324 was observed in VF-carrot chips, pre-treated with CGG. This may be due to the formation of a thin layer

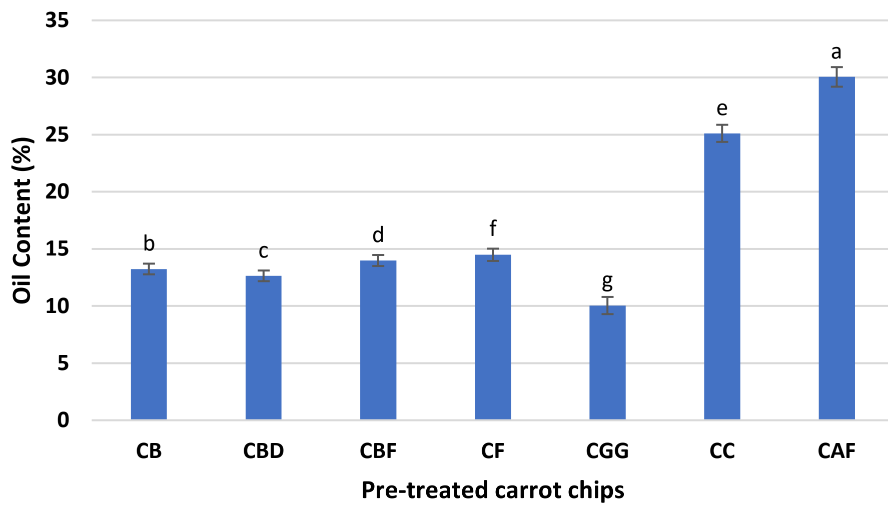

Figure 2. Effect of different pre-treatments on oil content of VF-carrot chips. Oil content (%) is presented with error bars representing standard deviations. Statistically significant differences between treatments are denoted by different letters (a, b, c, d, e, f and g), as determined by Tukey HSD post-hoc analysis ($p < 0.05$ for groups sharing the same letter); (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying).

of gum solution over the chips, leading to high moisture content in the chips (Ayustaningwarno et al., 2018; Manoharan et al., 2024). Guar gum, a high-molecular-weight polysaccharide composed of galactomannan units, plays a key role in this phenomenon. It has a high affinity for water due to its hydrophilic nature, enabling it to form hydrogen bonds with water molecules. When guar gum is applied as a coating, its galactose side chains and mannose backbone interact with water, creating a gel-like network that immobilizes water molecules and reduces their availability for evaporation or microbial activity. This binding mechanism contributes to the higher water activity observed in guar gum-coated samples compared to other pre-treatments (Yu et al., 2016; Salehi et al., 2021). Conversely, the lowest water activity was noticed for VF-carrot chips (0.214), pre-treated with CBD. This may be caused by moisture removal during drying (Fan et al., 2006). The moisture content and water activity of the chips exhibited the same trend concerning the pre-treatments. The observed water activity values of VF-carrot chips were below the threshold limit and considered safe. The results obtained were supported by studies carried out by Ren et al. (2018) and Perez-Tinoco et al. (2008), who observed the closest values of a_w for VF-shiitake mushroom chips (0.38 a_w) and pineapple chips (0.29 a_w), respectively. Ren et al. (2018) observed that both vacuum frying and atmospheric frying exhibited safe levels of water activity values for storage.

3.4 Hardness of VF-carrot chips

The texture of VF-carrot chips, measured as hardness, is a critical factor in sensory evaluation. A lower hardness value generally indicates higher crispiness, which is a desirable attribute for fried snacks. The hardness of the pre-treated VF-carrot chips is

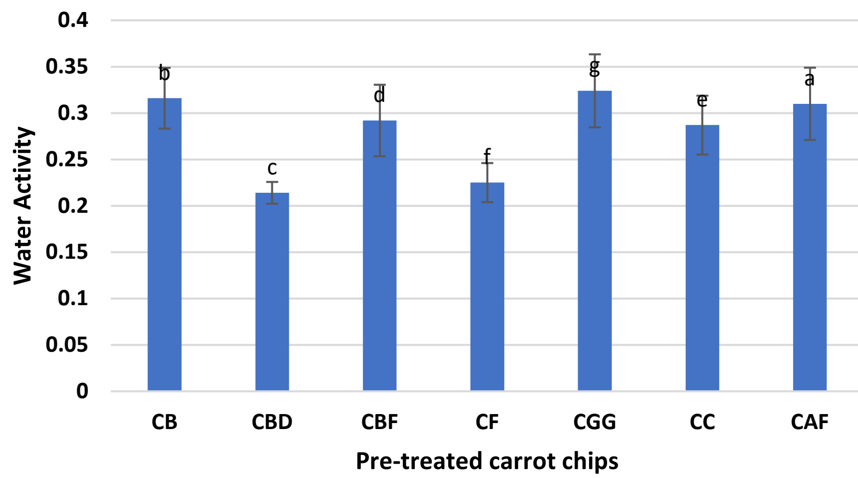

Figure 3. Effect of different pre-treatments on water activity of VF-carrot chips. Water activity is presented with error bars representing standard deviations. Statistically significant differences between treatments are denoted by different letters (a, b, c, d, e, f and g), as determined by Tukey HSD post-hoc analysis ($p < 0.05$ for groups sharing the same letter); (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying).

depicted in Figure 4. From Figure 4, it is observed that the hardness of VF-carrot chips ranged from 1.282 to 1.969 N. The lowest hardness of 1.212 N was obtained in VF-carrot chips pre-treated with CF. It was stated that during the frying of frozen treated samples, free water between the cells vaporized, and the interspaces left by water evaporation expanded, resulting in an increase in porosity and reduction in hardness (van der Sman & Schenk, 2024). Praveena et al. (2024) reported that VF-jackfruit chips had obtained a lower hardness value for frozen pre-treated samples. In vacuum-fried carrot chips, hardness is inversely related to moisture content. Lower moisture content results in less water acting as a plasticizer in the food matrix, leading to increased structural rigidity and higher hardness values. For instance, the lowest moisture content (2.15%) observed in carrot chips pre-treated with blanching combined with drying (CBD) corresponded to the highest hardness value (1.969 N). Conversely, chips pre-treated with freezing (CF), which retained slightly higher moisture (2.67%), exhibited the lowest hardness value (1.282 N). This trend was consistent with prior studies indicating that dehydration processes reduce the water content, thereby increasing the density and compactness of the food matrix, leading to greater resistance to mechanical deformation (Fan et al., 2006; Maity et al., 2014). The highest hardness value of 1.969 N was noted in VF-carrot chips, pre-treated with CBD. This was caused by the removal of moisture before frying, making the chips compact and hard. Praveena et al. (2024) reported that samples of low hardness values (breaking force) were of high crispiness. The ascending order of hardness values of VF-carrot chips from other pre-treatments viz., CBF, CB, and CGG were 1.432 N, 1.512 N, and 1.358 N, respectively. The CC and CAF chips had hardness values of 1.301 N and 1.452 N which were lower than the CGG VF-carrot chips. The effect of pre-treatments had a significant ($p < 0.05$) effect on the hardness of the VF-carrot chips.

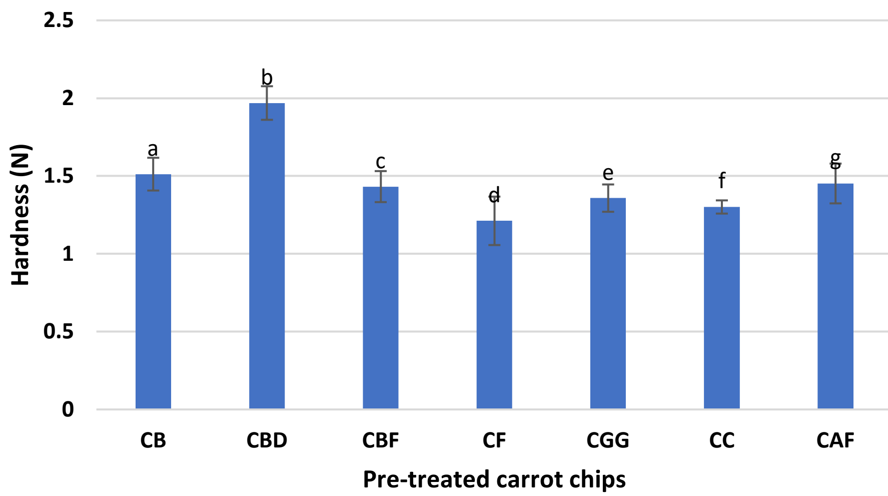

Figure 4. Effect of different pre-treatments on hardness of VF-carrot chips. Hardness (N) is presented with error bars representing standard deviations. Statistically significant differences between treatments are denoted by different letters (a, b, c, d, e, f and g), as determined by Tukey HSD post-hoc analysis ($p < 0.05$ for groups sharing the same letter); (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying).

3.5 Color values of VF-carrot chips

The color of the VF-carrot chips, expressed by L* (lightness), a* (redness), and b* (yellowness) values, strongly influences visual appeal, which is a key factor in sensory evaluation. The color values (L*, a*, and b*) of the VF-carrot chips varied significantly ($p < 0.05$) with different pre-treatments, as shown in Table 1. The mechanisms behind color changes during each pre-treatment are influenced by temperature, moisture content, and the retention of pigments. Blanching (CB) helps in enzyme inactivation, reducing oxidative browning but may lead to carotenoid loss, contributing to a decrease in L* and b* values. The subsequent drying in blanching combined with drying (CBD) increases the concentration of pigments due to moisture reduction, enhancing L* and a* values but can decrease b* values due to the loss of water-soluble pigments. Freezing after blanching (CBF) preserves the natural color by limiting enzyme activity and oxidation, resulting in higher a* and b* values. Freezing alone (CF) also helps maintain color, as it prevents pigment degradation, resulting in lighter and more vibrant chips. The edible gum coating (CGG) forms a protective barrier that reduces oxidation and moisture loss during frying, leading to better color retention, as seen in higher L* and b* values. These mechanisms are supported by studies that highlight the impact of pre-treatment conditions on pigment stability and overall color quality of fried products (Fan et al., 2006; Praveena et al., 2024). Figure 5 represents the effects of the color values of pre-treated VF-carrot chips. From Table 1, it is observed that the CF pre-treated VF-carrot chips recorded a maximum L* (lightness) value (38.92±1.22), followed by CBF (37.38±1.05), CC (37.08±1.20), CB (36.37±1.12), and CGG (35.15±1.18) chips. The CF pre-treatment produced light-

Table 1. Effect of pre-treatments on the color values (L*, a*, b*, and ΔE) of VF-carrot chips (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying)

Pre-Treatment	L* (Lightness)	a* (Redness)	b* (Yellowness)	ΔE (Color Difference)
CB	36.37 ± 1.12^{b}	18.02 ± 0.85^{b}	23.28 ± 1.02^{c}	13.98 ± 0.90^{b}
CBD	34.58 ± 1.35^{c}	17.24 ± 0.92^{c}	19.91 ± 1.08^{d}	20.89 ± 1.10^{a}
CBF	37.38 ± 1.05^{ab}	20.42 ± 0.78^{a}	26.71 ± 1.15^{b}	11.41 ± 0.88^{c}
CF	38.92 ± 1.22^{a}	22.85 ± 0.90^{a}	27.86 ± 1.10^{a}	11.15 ± 0.75^{c}
CGG	35.15 ± 1.18^{bc}	18.61 ± 0.87^{b}	23.94 ± 1.05^{c}	16.43 ± 0.95^{b}
CC	37.08 ± 1.20^{ab}	21.87 ± 0.85^{a}	25.48 ± 1.08^{b}	12.15 ± 0.82^{c}
CAF	30.20 ± 1.40^{d}	16.44 ± 0.88^{c}	20.28 ± 1.12^{d}	22.80 ± 1.25^{a}

Note: Different superscript letters (a, b, c, d) indicate significant differences ($p < 0.05$) as determined by Tukey HSD post-hoc analysis.

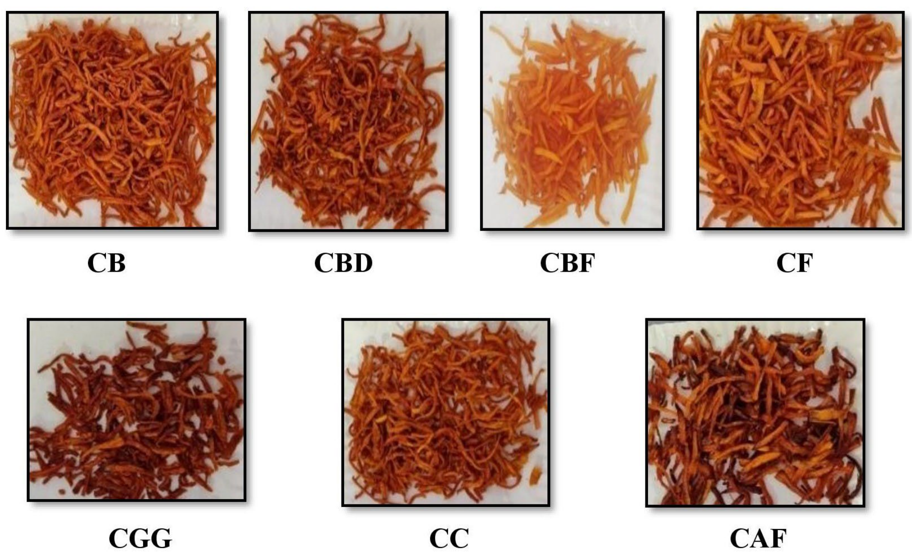

Figure 5. Final appearance of VF-carrot chips (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying)

colored chips; a desirable characteristic for acceptance by consumers. CAF chips had the lowest L* value (30.20 ± 1.40), followed by CBD pre-treatment (34.58 ± 1.35). The low L* value in CAF chips resulted from non-uniform frying and frying at high temperatures, resulting in dark-colored chips. The final appearance of pre-treated VF-carrot chips is shown in Figure 5 to visually demonstrate the variations in their color. Fan et al. (2006) stated that the L* value decreased in blanching combined with drying pre-treatment due to the loss of carotene content by air drying. Carotene content imparts yellowness and redness to the carrot chips. The color of vacuum-fried carrot chips is closely related to the retention of carotenoids, which are the primary pigments responsible for the orange and yellow hues. Carotenoids, including beta-carotene, contribute significantly to the L* (lightness), a* (redness), and b* (yellowness) values observed in the samples. Higher carotene content generally correlates with more vibrant and intense color values. For a* (redness), the highest value was recorded in CF pre-treated chips (22.85±0.90[a]), followed by CC (21.87±0.85), CBF (20.42±0.78), CGG (18.61±0.87), and CBD (17.24±0.92). The higher redness in CF-treated samples may be attributed to the preservation of carotenoid pigments during the freezing process. Chips treated with CAF had the lowest a* value (16.44±0.88), likely due to pigment loss and uneven frying conditions. The b* value of the VF-carrot chips was observed to be maximum for the CF (27.86±1.10) pre-treatment, followed by CBF (26.71±1.15), CC (25.48±1.08), CGG (23.94±1.05), CB (23.28±1.02), and CAF (20.28±1.12). The minimum b* value was observed in the VF-carrot chips for CBD pre-treatment (19.91±1.08). The decrease in b* values might be due to the reduction of carotenes present in the carrot. The change in ΔE (color difference) was comparatively less in CF (11.15±0.75) and CBF (11.41±0.88), suggesting that these treatments preserved the natural color of the carrot chips, whereas the highest color change (22.80±1.25[a]) was observed in CAF, reflecting significant color alterations due to higher frying temperatures. Praveena et al. (2024) reported similar results on the color analysis of vacuum and atmospheric fried jackfruit chips.

3.6 Sensory analysis

The sensory evaluation was conducted to assess the texture, color, flavor, taste, and overall acceptability of the vacuum-fried carrot chips. A panel of 15 judges was selected based on their prior experience in sensory analysis and their ability to evaluate food products. The judges were screened for normal sensory acuity (i.e., no known smell or taste impairments) to ensure reliable and consistent evaluations.

Prior to the sensory evaluation, the judges underwent a brief training session, where they were familiarized with the specific sensory attributes they were to evaluate. They were trained on how to use the nine-point hedonic scale for rating each attribute. This training ensured consistency across evaluations and allowed the panelists to become accustomed to the product characteristics being assessed.

All samples were served at room temperature (approximately 24°C) to maintain consistency and eliminate any temperature bias. The samples were presented to the judges in a random order to minimize any potential order effects during the evaluation process.

The sensory scores of VF-carrot chips with various pre-treatments are shown in Figure 6. The highest sensory scores were noted for pre-treated VF-carrot chips compared to the CC and CAF. The pre-treatments CF (9.0) and CBF (8.7) were noted for their highest overall acceptability, followed by other pre-treatments, namely CB (8.3) and CBD (7.6) for VF-carrot chips. The lowest sensory score was observed in CAF (5.8), followed by CGG (6.1) and the CC (6.7) chips. For the CF pre-treated sample, all sensory attributes such as color and appearance (8.8), texture (8.6), flavour (8.5), taste (8.8), and overall acceptability (9.0) were recorded as the highest values. Chips pre-treated with freezing (CF) exhibited the lowest hardness (1.282 N), which corresponded to their highest sensory scores for texture (8.6) and overall acceptability (9.0). Conversely, pre-treatments like blanching

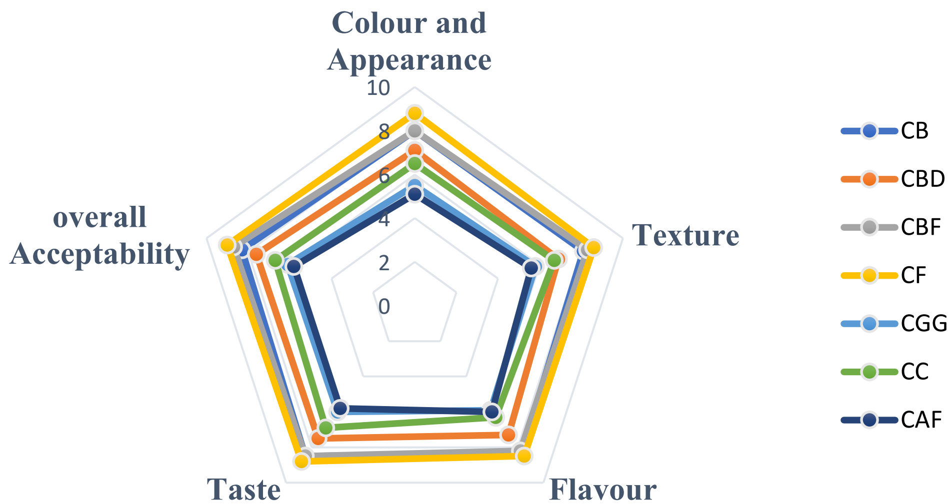

Figure 6. Effect of pre-treatment on sensory scores of VF-carrot chips (CB: Carrot with blanching; CBD: Carrot with blanching cum drying; CBF: Carrot with blanching cum freezing; CF: Carrot with freezing; CGG: Carrot with edible gum coating; CC: Carrot untreated (control sample); CAF: Carrot with atmospheric frying)

combined with drying (CBD) resulted in higher hardness, leading to lower sensory ratings due to the chips having a less crispy and more compact texture. Also, CF pre-treated chips displayed the highest L* value (38.92), indicating a light and appealing appearance, which was highly rated by the sensory panel (color and appearance score: 8.8). Chips with darker or less vibrant colors, such as those treated with atmospheric frying (CAF), had lower sensory scores, likely due to uneven frying and non-uniform color. The CBF and CB pre-treatment chips had similar values. The CF pre-treated VF-carrot chips exhibited superior quality characteristics compared to other pre-treated samples.

4. Conclusions

In this study, the effects of various pre-treatment methods on the quality attributes of vacuum-fried (VF) carrot chips were evaluated. Among all the pre-treatments, freezing (CF) emerged as the most effective method, yielding chips with superior sensory characteristics (overall acceptability score: 9.0), lower hardness (1.282 N), and better color retention (L*: 38.92 ± 1.22^a, a*: 22.85 ± 0.90^a, b*: 27.86 ± 1.10^a; $p<0.05$). The lowest oil content (10.04%) was observed in edible gum-coated chips (CGG), and blanching combined with drying (CBD) resulted in the lowest moisture content (2.15%) and water activity (0.214). These findings indicate that vacuum-frying with appropriate pre-treatments can produce high-quality, healthier carrot chips with reduced oil uptake and prolonged shelf stability, offering significant potential for commercial snack production.

5. Acknowledgements

The authors gratefully acknowledge the Department of Processing and Food Engineering, Kelappaji College of Agricultural Engineering and Technology (KCAET), Kerala Agricultural University (KAU), Tavanur, Kerala, India, for providing the necessary facilities and support to carry out the research work.

6. Authors' Contributions

Puletipalli Babu: Conceptualization, methodology, experimental design, manuscript writing; Deepanka Saikia: Supervision, validation, formal analysis, manuscript editing and review; Rajesh G K: Supervision, Data analysis, statistical validation, technical support; Prakash Kumar Nayak: Investigation, data curation, manuscript review; Sudheer K P: Technical guidance, experimental validation; and Jinukala Srinivas: Laboratory support, manuscript proofreading.

7. Conflicts of Interest

The authors declare no conflict of interest in this work.

ORCID

Puletipalli Babu https://orcid.org/0000-0002-0171-9864
Deepanka Saikia https://orcid.org/0000-0003-0808-5400
Prakash Kumar Nayak https://orcid.org/0000-0001-5811-6629
Jinukala Srinivas https://orcid.org/0000-0003-4213-1749

References

Al Faruq, A., Khatun, M. H. A., Azam, S. M. R., Sarker, M. S. H., Mahomud, M. S., & Jin, X. (2022). Recent advances in frying processes for plant-based foods. *Food Chemistry Advances*, 1, Article 100086. https://doi.org/10.1016/j.focha.2022.100086

AOAC. (2019). *Official methods of analysis of AOAC international*. *Vol. 1* (21st Ed.). AOAC.

Ayustaningwarno, F., Dekker, M., Fogliano, V., & Verkerk, R. (2018). Effect of vacuum frying on quality attributes of fruits. *Food Engineering Reviews*, 10(3), 154-164. https://doi.org/10.1007/s12393-018-9178-x

Bouchon, P., & Dueik, V. (2018). Frying of foods. In A. Rosenthal, R. Deliza, J. Welti-Chanes, & G. Barbosa-Cánovas (Eds.). *Fruit preservation* (pp. 275-309). Springer. https://doi.org/10.1007/978-1-4939-3311-2_10

Camelo, A. F. L. (2004). *Manual for the preparation and sale of fruits and vegetables*. From field to market. FAO.

Chen, J., Venkitasamy, C., Shen, Q., McHugh, T. H., Zhang, R., & Pan, Z. (2018). Development of healthy crispy carrot snacks using sequential infrared blanching and hot air drying method. LWT, 97, 469-475. https://doi.org/10.1016/j.lwt.2018.07.026

Dueik, V., Robert, P., & Bouchon, P. (2010). Vacuum frying reduces oil uptake and improves the quality parameters of carrot crisps. *Food Chemistry*, 119(3), 1143-1149. https://doi.org/10.1016/j.foodchem.2009.08.027

Fan, L.-P., Zhang, M., & Mujumdar, A. S. (2006). Effect of various pre-treatments on the quality of vacuum-fried carrot chips. *Drying Technology*, 24(11), 1481-1486. https://doi.org/10.1080/07373930600952826

Gouyo, T., Rondet, É., Mestres, C., Hofleitner, C., & Bohuon, P. (2021). Microstructure analysis of crust during deep-fat or hot-air frying to understand French fry texture. *Journal of Food Engineering*, 298, Article 110484. https://doi.org/10.1016/j.jfoodeng.2021.110484

Ikram, A., Rasheed, A., Khan, A. A., Khan, R., Ahmad, M., Bashir, R., & Mohamed, M. H. (2024). Exploring the health benefits and utility of carrots and carrot pomace: a systematic review. *International Journal of Food Properties*, 27(1), 180-193. https://doi.org/10.1080/10942912.2023.2301569

Kurian, A. E., Rao, P. G. P., Nagender, A., Srinivasulu, K., & Mala, K. S. (2021). Studies on development of instant pumpkin soup tablets and evaluation of storage stability. *Indian Journal of Traditional Knowledge*, 20(2), 486-491.

Liu, Y., Tian, J., Zhang, T., & Fan, L. (2021). Effects of frying temperature and pore profile on the oil absorption behavior of fried potato chips. *Food Chemistry*, 345, Article 128832. https://doi.org/10.1016/j.foodchem.2020.128832

Maity, T., Bawa, A. S., & Raju, P. S. (2014). Effect of vacuum frying on changes in quality attributes of jackfruit (*Artocarpus heterophyllus*) bulb slices. *International Journal of Food Science*, 2014, Article 752047. https://doi.org/10.1155/2014/752047

Manjunatha, S. S., Ravi, N., Negi, P. S., Raju, P. S., & Bawa, A. S. (2014). Kinetics of moisture loss and oil uptake during deep fat frying of Gethi (*Dioscorea kamoonensis* Kunth) strips. *Journal of Food Science and Technology*, 51(11), 3061-3071. https://doi.org/10.1007/s13197-012-0841-6

Manoharan, S., Dubey, P. K., & Sharma, M. (2024). Recent advances in deep‐fat frying through pre-treatments and edible coating to reduce oil absorption. *Journal of Food Process Engineering*, 47(8), Article e14706. https://doi.org/10.1111/jfpe.14706

Mesias, M., Delgado-Andrade, C., Holgado, F., González-Mulero, L., & Morales, F. J. (2021). Effect of consumer's decisions on acrylamide exposure during the preparation of French fries. Part 1: Frying conditions. *Food and Chemical Toxicology*, 147, Article 111857. https://doi.org/10.1016/j.fct.2020.111857

Pathare, P. B., Opara, U. L., & Al-Said, F. A.-J. (2013). Colour measurement and analysis in fresh and processed foods: A review. *Food and Bioprocess Technology*, 6(1), 36-60. https://doi.org/10.1007/s11947-012-0867-9

Pedreschi, F. (2012). Frying of potatoes: Physical, chemical, and microstructural changes. *Drying Technology*, 30(7), 707-725. https://doi.org/10.1080/07373937.2012.663845

Perez-Tinoco, M. R., Perez, A., Salgado-Cervantes, M., Reynes, M., & Vaillant, F. (2008). Effect of vacuum frying on main physicochemical and nutritional quality parameters of pineapple chips. *Journal of the Science of Food and Agriculture*, 88(6), 945-953. https://doi.org/10.1002/jsfa.3171

Praveena, N., Surya, R., Fairoosa, K., Rajesh, G. K., George, A. K., & Tasneem, S. A. F. (2024). Development and quality evaluation of vacuum fried jackfruit (*Artocarpus heterophyllus*) chips. *Asian Journal of Dairy and Food Research*, 43(1), 116-123. https://doi.org/10.18805/ajdfr.DR-1549

Ranasalva, N., & Sudheer, K. P. (2017). Effect of pre-treatments on quality parameters of vacuum fried ripened banana (Nendran) chips. *Journal of Tropical Agriculture*, 55(2), 161-166.

Ren, A., Cao, Z., Tang, X., Duan, Z., Duan, X., & Meng, X. (2022). Reduction of oil uptake in vacuum fried *Pleurotus eryngii* chips via ultrasound assisted pre-treatment. *Frontiers in Nutrition*, 9, Article 1037652. https://doi.org/10.3389/fnut.2022.1037652

Ren, A., Pan, S., Li, W., Chen, G., & Duan, X. (2018). Effect of various pre-treatments on quality attributes of vacuum-fried shiitake mushroom chips. *Journal of Food Quality*, 2018, Article 4510126. https://doi.org/10.1155/2018/4510126

Ruiz-Capillas, C., & Herrero, A. M. (2021). Sensory analysis and consumer research in new product development. *Foods*, 10(3), Article 582. https://doi.org/10.3390/foods10030582

Saikia, D., Nayak, P. K., Boruha, B., Krishnan, K. R., Dash, U., & Bal, L. M. (2022). Effect of pre-drying and microwave-assisted vacuum frying on elephant apple. *Journal of Scientific and Industrial Research*, 81(9), 989-994. https://doi.org/10.56042/JSIR.V81I09.58829

Saini, R., Kaur, S., Aggarwal, P., & Dhiman, A. (2023). The influence of conventional and novel blanching methods on potato granules, phytochemicals, and thermal properties of colored varieties. *Frontiers in Nutrition*, 10, Article 1178797. https://doi.org/10.3389/fnut.2023.1178797

Salehi, F., Roustaei, A., & Haseli, A. (2021). Effect of surface coating with seeds mucilages and xanthan gum on oil uptake and physical properties of fried potato strips. *Food Science and Nutrition*, 9(11), 6245-6251. https://doi.org/10.1002/fsn3.2583

Santos, J. S. P. D., Leonel, M., de Jesus, P. R. R., Leonel, S., Fernandes, A. M., & dos Ouros, L. F. (2023). Hydrocolloid coatings as a pre-frying treatment in the production of low-fat banana chips. *Horticulturae*, 9(10), Article 1139. https://doi.org/10.3390/horticulturae9101139

Tapia, M. S., Alzamora, S. M., & Chirife, J. (2020). Effects of water activity (a_w) on microbial stability as a hurdle in food preservation. In G. V. Barbosa-Cánovas, A. J. Fontana Jr., S. J. Schmidt, & T. P. Labuza. *Water activity in foods: Fundamentals and applications* (pp. 323-355). Wiley. https://doi.org/10.1002/9781118765982.ch14

Udomkun, P., & Innawong, B. (2018). Effect of pre-treatment processes on physicochemical aspects of vacuum-fried banana chips. *Journal of Food Processing and Preservation*, 42(8), Article e13687. https://doi.org/10.1111/jfpp.13687

van der Sman, R. G. M., & Schenk, E. (2024). Causal factors concerning the texture of French fries manufactured at industrial scale. *Current Research in Food Science*, 8, Article 100706. https://doi.org/10.1016/j.crfs.2024.100706

Yan, W.-Q., Zhang, M., Huang, L.-L., Mujumdar, A. S., & Tang, J. (2013). Influence of microwave drying method on the characteristics of the sweet potato dices. *Journal of Food Processing and Preservation*, 37(5), 662-669. https://doi.org/10.1111/j.1745-4549.2012.00707.x

Yeshiwas, Y., & Tadele, E. (2021). An investigation into major causes for postharvest losses of horticultural crops and their handling practice in Debre Markos, North-Western Ethiopia. *Advances in Agriculture*, 2021, Article 1985303. https://doi.org/10.1155/2021/1985303

Yu, L., Li, J., Ding, S., Hang, F., & Fan, L. (2016). Effect of guar gum with glycerol coating on the properties and oil absorption of fried potato chips. *Food Hydrocolloids*, 54, 211-219. https://doi.org/10.1016/j.foodhyd.2015.10.003