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EMERGING INVESTIGATORS

Article

Pressing filtration for extraction of cabbage dietary fiber and soluble components

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SUMMARY

Dietary fiber plays a vital role in human health by promoting bowel regularity, reducing the risk of cardiovascular disease and diabetes, and supporting overall digestive function. However, many individuals fail to meet daily fiber intake recommendations, largely due to the limited fiber content of commonly consumed foods. Addressing this nutritional gap requires innovative approaches for producing high-fiber food ingredients that are both effective and palatable. In this study, we introduce pressing filtration as an efficient, low-energy method for extracting dietary fiber from cabbage. Unlike conventional drying or enzymatic methods, pressing filtration retains heat-sensitive nutrients and achieves a high fiber yield without compromising flavor. Notably, the resulting cabbage powder can be incorporated into foods such as hamburger buns and beef patties without altering their taste or sensory quality. By operating on the same principle as an industrial high-pressure diaphragm filter press, this study demonstrates the scalability and economic viability of the pressing filtration method for future commercial applications to enhance fiber content in familiar foods, offering a promising solution to improve dietary fiber intake and support public health nutrition.

INTRODUCTION

Dietary fiber plays a crucial role in human health, offering numerous benefits, including promoting bowel regularity, enhancing digestive function, reducing constipation, diluting or facilitating the removal of waste in food via adsorption, preventing colon cancer, and maintaining and controlling blood sugar and cholesterol levels (1). A lack of dietary fiber in the human body can lead to an increased risk of colon cancer, coronary heart disease, diabetes, and obesity (1, 2). Consequently, dietary fiber is referred to as the seventh most important nutrient, following carbohydrates, fats, proteins, water, vitamins, and inorganic salts (3). The Dietary Guidelines for Americans recommends a daily total dietary fiber intake of 25 to 31 g for adults, yet more than 90% of women and 97% of men fail to meet these recommended intakes (4).

Cabbage, one of the least expensive vegetables in American supermarkets, is rich in dietary fiber, minerals, and vitamins essential for human health (5). It exhibits anti-genotoxic, antioxidant, and anti-cytotoxic properties, effectively helping to prevent inflammatory diseases, cancer, and heart disease, among other conditions (6-8). Cabbage contains 2.5 g of dietary fiber per 100 g, making it a good source of dietary fiber (5). Consuming sufficient dietary fiber from raw cabbage alone would require over 1,000 g daily, which is unrealistic for regular diets. This underscores the importance of developing efficient techniques to concentrate the dietary fiber from cabbage into fiber-poor foods such as refined carbohydrates or meat-based products, such as commonly consumed items like hamburgers, at a low cost and without altering the original flavor and texture (9).

Current methods for extracting dietary fiber from cabbage primarily include drying, high-pressure homogenization, and enzymatic processes (10-13). However, these methods present several limitations. Drying methods are energy-intensive, costly, and inefficient due to the high-water content of cabbage (92.2%; 5). In addition, the drying process retains a significant amount of flavor compounds in the cabbage powder (14), potentially altering the original taste of foods to which it is added, thus affecting consumer acceptance. Enzymatic hydrolysis offers targeted breakdown and improved yield but relies on costly enzymes and prolonged reaction times, making it economically challenging for large-scale applications (13). Similarly, pressure homogenization requires high mechanical energy and specialized equipment, limiting its feasibility in cost-sensitive production environments (12). As a result of these limitations, these methods have not yet been implemented in industrial production.

To address these challenges, we investigated pressing filtration as an alternative dietary fiber extraction method that combines squeezing and filtration into one to separate solid and liquid components. Pressing filtration, a low-energy method for fiber enrichment, is therefore explored in this study for its potential to enhance fiber yield while maintaining functional properties. This approach would enable individuals, particularly those in low-income groups who rely on such foods as their staple diet, to obtain sufficient dietary fiber nutrition from these enhanced products.

We hypothesized that pressing filtration would enhance fiber yield while preserving fiber functionality, offering a cost-effective alternative to the traditional drying method. Our research confirms that pressing filtration flow can produce high dietary fiber content cabbage powder, and yields a palatable cabbage juice beverage. Most flavor compounds are transferred to the cabbage juice, leaving the cabbage powder nearly flavorless, allowing the powder to be added to foods without altering their original taste. Further, utilizing existing high-pressure diaphragm filter press technology would enable low-cost and high-efficiency industrial production (15, 16). Our findings also confirm the feasibility and versatility of pressing filtration for scalable, low-cost dietary fiber extraction, offering both nutritional and industrial advantages for food applications.

https://doi.org/10.59720/25-061

RESULTS

Blanching Temperature and Duration Significantly Affect the Sensory Quality of Cabbage Juice

We first blanched the cabbage at five temperatures (50 °C, 60 °C, 70 °C, 80 °C, and 90 °C) for five durations (4, 6, 8, 10, and 12 minutes). Balancing was followed by filtration a sensory evaluations of the resulting cabbage juice. Our analyses indicated that both blanching temperature and time had significant effects on sensory scores, with a highly significant interaction effect also observed (two-way ANOVA, $F(4) = 1283.27$, $F(4) = 690.77$, $F(16) = 69.74$ for temperature, time, and interaction, respectively, all $p < 0.001$; **Figure 1**). We selected a sensory panel that consisted of 15 trained participants who were interested in this study and served as judges of the sensory effects. Each sample was evaluated in triplicate. Based on the results of the panel, cabbage juice blanched at 80 °C for 10 minutes was rated as highly palatable without a spicy taste, corresponding to the 81–100 range on the hedonic scale. The subsequent experiments adopted this condition as the optimized blanching treatment.

Pressing Pressure and Duration Determine the Dietary Fiber Yield from Cabbage Filter Cake

To test our hypothesis that pressing filtration would enhance fiber yield while offering alternative to the traditional drying method, we press-filtrated the cabbage that had been blanched under the optimized conditions (80 °C for 10 minutes) at the pressures of 0.608 MPa (5 tons), 0.729 MPa (6 tons), 0.851 MPa (7 tons), 0.972 MPa (8 tons), and 1.09 MPa (9 tons).and at 30, 60, 90, 120, and 150 minutes, respectively, and tested the dietary fiber content of the obtained cabbage filter cakes. The contents of total dietary fiber (TDF), insoluble dietary fiber (IDF), and soluble dietary fiber (SDF) in the cabbage filter cake increased significantly with higher pressing pressure and longer filtration duration. These increasing trends were confirmed (two-way ANOVA, $F(4) = 196.56$, 128.52, and 44.41 for TDF, IDF, and SDF, respectively, with temperature, $F(5) = 1663.67$, 1504.01, and 127.29 for TDF, IDF, and SDF, respectively, with duration, $p < 0.001$ for all factors; **Figure 2**). However, when the pressure reaches 0.972 MPa and the duration exceeds 90 minutes, further increases in these parameters yield only marginal improvements in fiber content, with no statistical significance ($p > 0.05$). Consequently, 0.972 MPa and 90 minutes were identified as the optimal pressure and duration for the pressing filtration process, respectively.

Under these optimized conditions, the content of TDF, IDF, and SDF in the cabbage filter cake reached 23.08%, 17.51%, and 5.57%, respectively. These values are expressed on a wet weight basis, calculated directly from the weight of the unprocessed cabbage prior to drying. The optimized parameters (0.972 MPa pressure and 90-minute duration) were subsequently employed for all pressing filtration procedures in the ensuing experiments.

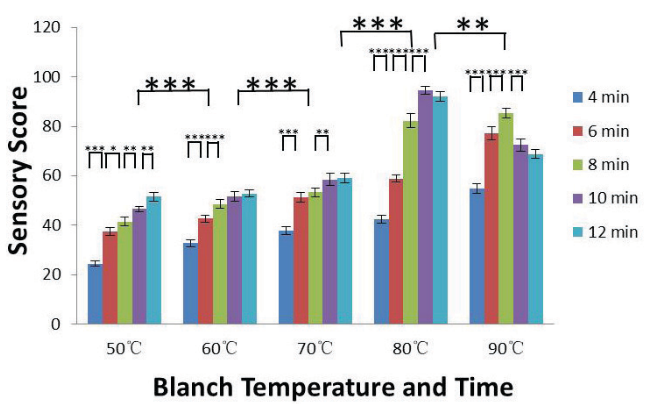

Figure 1: The effect of the temperature and time of blanching on cabbage juice sensory score. The data were presented as mean ± 95%CI (n=3×15). Two-way analysis of variance (ANOVA) revealed that the effects of temperature ($F(4)=1283.27$, $p < 0.001$) and time ($F(4) = 690.77$, $p < 0.001$) on sensory scores were significant. Additionally, a significant interaction effect between temperature and time was observed ($F(16)=69.74$, $p < 0.001$). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Cabbage Powder Addition Does Not Alter the Sensory Properties of Hamburger Buns and Patties

The tasteless cabbage powder, obtained by pulverizing the cabbage filter cake produced under optimized conditions was added to buns (0 g, 100 g, 200 g, 300 g, 400 g, and 500 g) containing 1kg flour and 1kg beef patties. These products were evaluated for taste and flavor by a sensory panel (**Figure 3**). The addition of cabbage powder at levels up to 40 g/100 g flour for buns and 30 g/100 g for beef patties did not result in statistically significant differences in flavor or taste compared to the control samples without cabbage powder ($p > 0.05$). These ratios also provided increased dietary fiber without affecting preparation time, indicating that a nutritional benefit can be achieved without compromising palatability or processing efficiency. The prepared hamburgers with these additional levels essentially maintained the original flavor and taste profile. Although no instrumental or quantitative texture analysis was conducted, no noticeable changes in texture were reported by the sensory panel, suggesting that the addition of cabbage powder did not negatively affect the mouthfeel or structural integrity of the final product.

Cabbage Powder Exhibits a High BET Surface Area and Porosity, Indicative of a Functional Fiber Structure

To evaluate the physicochemical properties of the cabbage powder obtained through pressing filtration, the sample was dried, sieved, and subjected to Brunauer–Emmett–Teller (BET) surface area and pore structure analysis. BET analysis is a widely used method for characterizing surface area and porosity, based on nitrogen adsorption. The cabbage powder exhibited a specific surface area of 1.90 m^2/g, a pore volume of 0.00576 cm^3/g, a most probable pore diameter of 1.98 nm, and an average pore diameter of 12.1 nm (**Figure 4**). These values demonstrate a porous, high-surface-area microstructure, which is a key physicochemical feature of functional dietary fibers (17). This structure enhances water retention and interaction with other food ingredients (17). While palatability was not directly linked to these metrics, the fine porosity and surface characteristics may support smoother incorporation and improved taste in food applications.

DISCUSSION

In this study, we optimized the processing parameters for cabbage powder and juice. Sensory evaluation was conducted to evaluate the sensory quality of cabbage juice,

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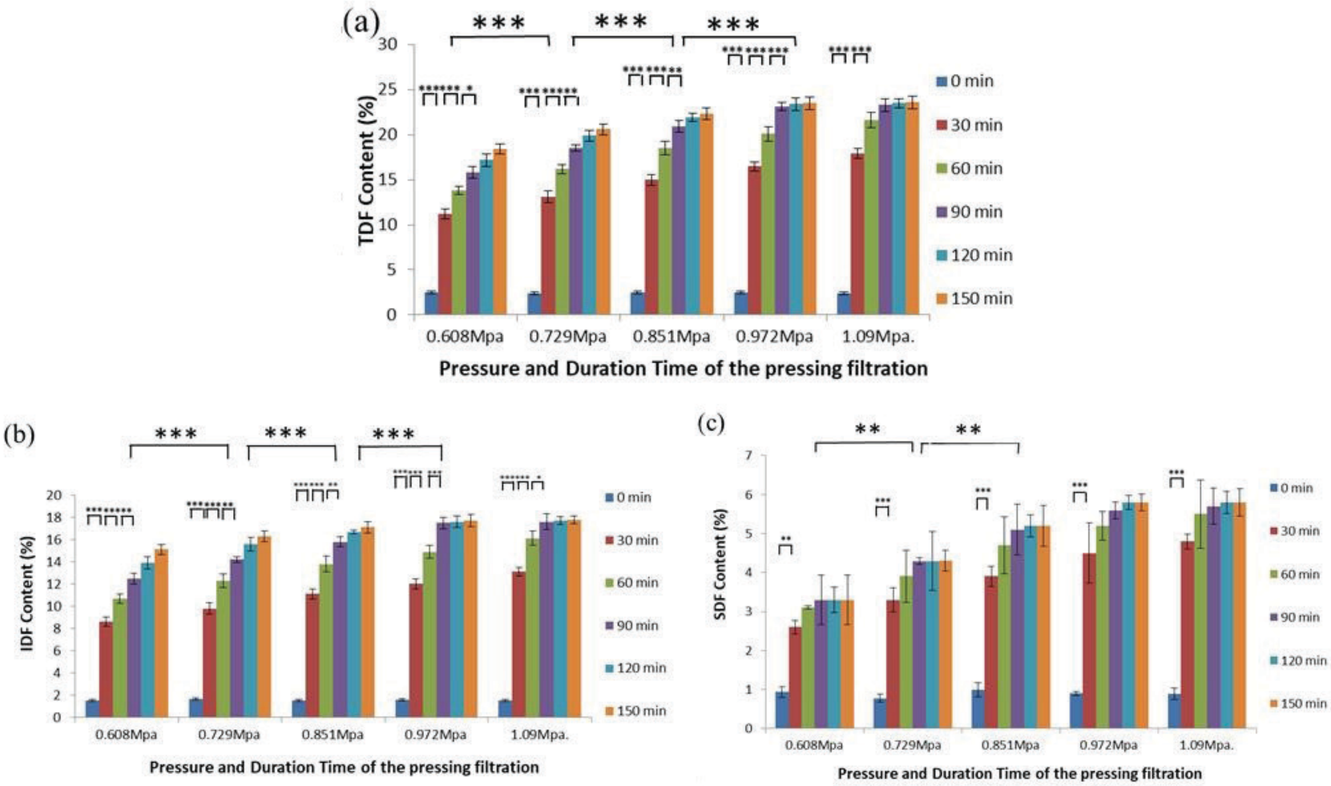

Figure 2: Effect of pressing pressure and duration on the dietary fiber content of cabbage filter cake. Pressing pressure and duration on the dietary fiber content for (a) total dietary fiber (TDF), (b) insoluble dietary fiber (IDF), and (c) soluble dietary fiber (SDF). Data are presented as mean ± SD (n = 3). Two-way ANOVA revealed a significant main effect of pressure (F(4)= 196.56, 128.52, and 44.41 for TDF, IDF, and SDF, respectively; all p < 0.001) and duration (F(5) = 1663.67, 1504.01, and 127.29; all *p* < 0.001), with corresponding partial η^2 values of 0.753, 0.687, and 0.384. Significant interaction effects were also observed (F(20)= 9.17, 6.57, and 1.87; *p* < 0.001 for TDF and IDF, *p* = 0.033 for SDF).*p < 0.05, **p < 0.01, ***p < 0.001.

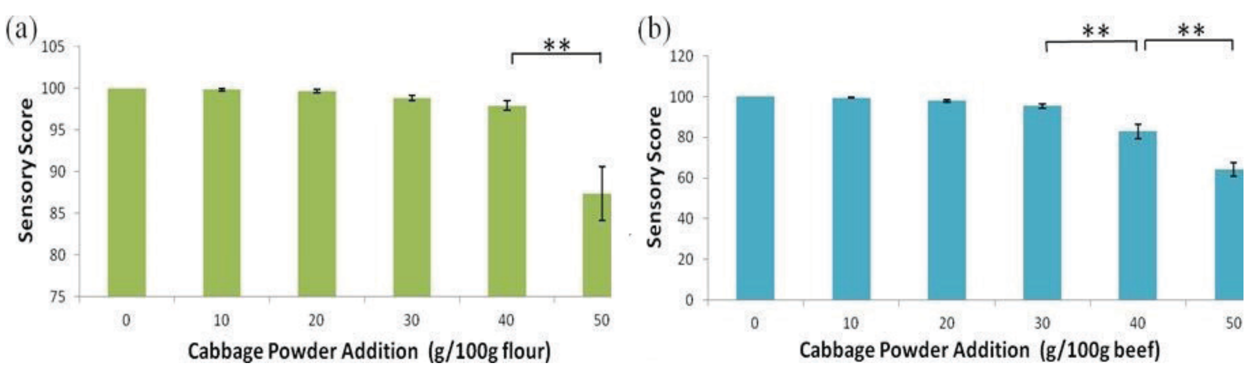

Figure 3: The effect of cabbage powder addition ratios on the taste and flavor. Cabbage powder addition ratios on the taste and flavor for (a) the buns and (b) the beef patties. The data were presented as mean ± 95%CI (*n*=3×15). One-way analysis of variance (ANOVA) revealed that the effects of cabbage powder addition ratios on sensory scores were extremely highly statistically significant (F = 50.25, 185.71 for buns and beef patties, respectively; all *p* < 0.001). *p < 0.05, **p < 0.01, ***p < 0.001.

and the results revealed that blanching at 80 °C for 10 minutes produced cabbage juice with the most favorable taste profile, as confirmed by significant main and interaction effects in two-way ANOVA. Pressing filtration of the blanched cabbage demonstrated that increasing pressure and duration significantly improved dietary fiber yield, with 0.972 MPa for 90 minutes identified as the optimal condition. Under these settings, the cabbage filter cake yielded high levels of total, insoluble, and soluble dietary fiber. The resulting cabbage powder, when incorporated into buns and beef patties, did not significantly alter sensory attributes, supporting its feasibility as a tasteless dietary fiber enhancer. Furthermore, BET analysis indicated a high surface area and porous microstructure of the cabbage powder, consistent with functional fiber properties.

Since cabbage juice is the inevitable byproduct of producing cabbage dietary fiber through pressing and filtration, this study also involved its preparation to ensure an

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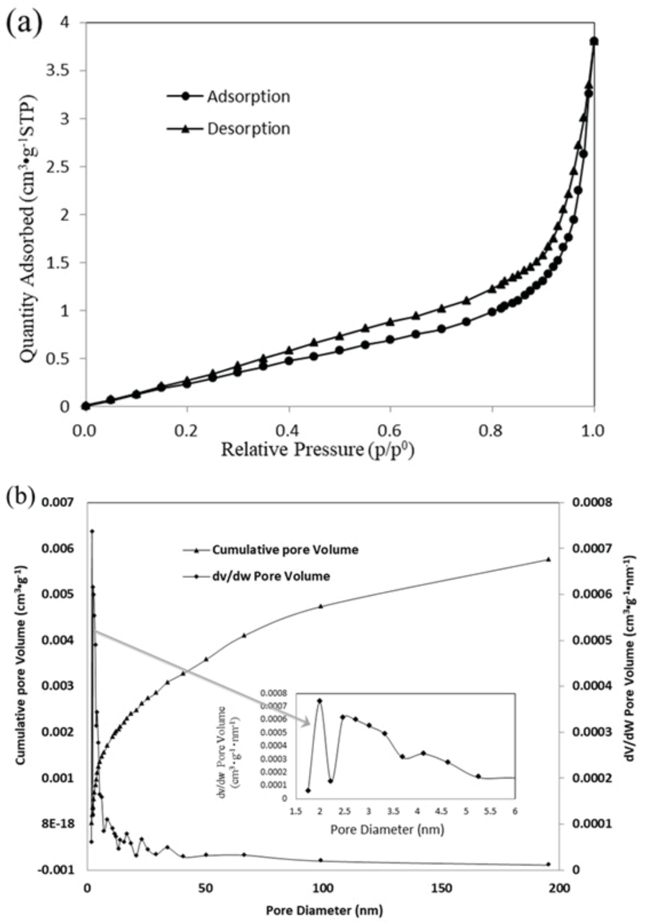

Figure 4: Nitrogen adsorption and desorption isotherm and pore size distribution of the cabbage powder. BET analysis was conducted to assess surface area and pore structure for (a) nitrogen adsorption and desorption isotherm and (b) pore size distribution, providing insight into its potential adsorption capacity.

acceptable taste for consumers. The taste of cabbage juice is primarily influenced by the blanching temperature and duration. When the temperature is too low and the blanching time is too short, the juice retains a pungent taste, likely due to sulfur-containing compounds such as isothiocyanates formed from glucosinolate breakdown (18). This spicy and acrid flavor is often considered unpleasant and unpalatable. On the other hand, excessive blanching (i.e., too high a temperature or prolonged exposure) can cause the loss of desirable sweet notes, resulting in a flat flavor that is generally less appealing. Additionally, high blanching temperatures may degrade some thermally sensitive nutrients such as vitamins (19-21). While dietary fiber is generally heat-resistant, structural alterations at high temperatures cannot be ruled out and may warrant further investigation. In our study, the blanching conditions were selected based on the highest sensory acceptance score rather than through chemical optimization. As we show, a blanching temperature of 80 °C and a duration of 10 minutes yielded cabbage juice with a sweet and pleasant flavor **(Figure 1)**.

The dual-output nature of the pressing filtration approach presents a notable industrial advantage. Unlike enzymatic methods that yield only soluble dietary fiber, pressing filtration simultaneously produces high-fiber cabbage powder and a palatable cabbage juice beverage, maximizing raw material utilization (12). This two-in-one output reduces waste and adds potential value streams for commercial applications, such as functional beverage development and clean-label fiber enrichment in food products. The scalability of this method is further supported by its compatibility with existing high-pressure diaphragm filter press systems, commonly used in the food and pharmaceutical industries (15).

Pressing filtration not only increased dietary fiber yield but also supported better nutrient retention by avoiding high-temperature drying, thus preserving heat-sensitive compounds such as vitamins and glucosinolates (21, 22). Under the optimized condition of 0.972 MPa for 90 minutes, the fiber content of cabbage filter cake reached 23.08% (wet weight), nearly tenfold higher than untreated cabbage (8). Compared with conventional drying, this method offers a low-cost, energy-efficient alternative with potential for industrial-scale production using existing diaphragm filter press equipment (**Figure 5**) (16).

An additional advantage of this process is flavor improvement: most water-soluble flavor compounds transfer into the juice, leaving the powder nearly tasteless. When incorporated into buns and patties at 40 g/100 g flour and 30 g/100 g beef, respectively, sensory properties remained unchanged while dietary fiber content increased, making two enriched hamburgers sufficient to meet daily fiber needs.

We also studied the important indicator of functional dietary fibers, the physicochemical properties of cabbage powder (17). Cabbage powder also exhibited favorable physicochemical properties, with a microporous structure (1.98 nm pore diameter) and relatively high BET surface area (1.90 m²/g). These characteristics suggest strong adsorptive capacity, supporting physiological functions such as cholesterol regulation and gut health (17, 23, 24). Overall, pressing filtration produces a nutrient-rich, functional dietary fiber powder and palatable cabbage juice, providing a practical strategy to transform low-cost fast food into healthier options without compromising flavor.

Although this study demonstrates the effectiveness of pressing filtration in enhancing dietary fiber yield and product palatability, it has several limitations. First, the sensory evaluation panel was limited to participants aged 18–30, which may not reflect broader consumer preferences across age groups. Second, the study focused solely on cabbage as a model vegetable, and the applicability of pressing filtration to other fiber-rich vegetables remains to be tested. Finally, no direct quantitative comparison was made between pressing filtration and other established fiber extraction methods, such as enzymatic hydrolysis or freeze-drying, which could further validate the relative efficiency of the proposed method.

In conclusion, our study presents an optimized pressing filtration process for extracting dietary fiber and cabbage juice, offering a promising alternative to traditional drying techniques. While direct comparisons were not conducted, the findings suggest that pressing filtration can yield high fiber content while retaining functional integrity and palatability. This dual-output approach improves material utilization and may reduce energy consumption, indicating practical advantages for industrial applications. These results indicate that pressing filtration is a viable and scalable method for producing dietary fiber ingredients and natural vegetable-based beverages,

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https://doi.org/10.59720/25-061

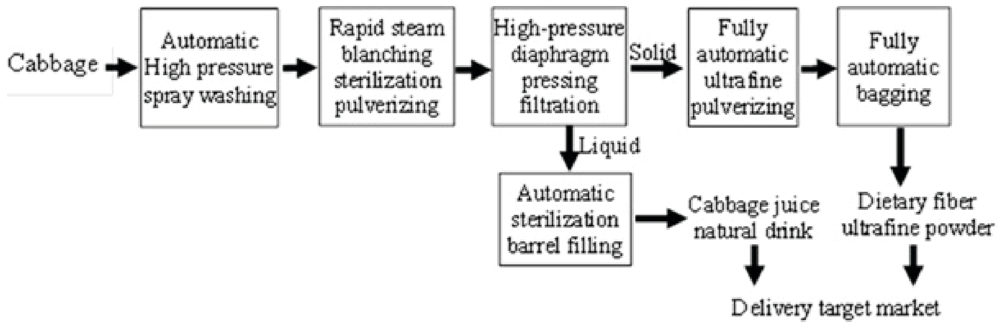

Figure 5: The industrial process flow of natural dietary fiber powder and natural beverage pressing production line from cabbage by filtration. The schematic illustrates the stepwise industrial process used to extract dietary fiber and cabbage juice via pressing filtration. The system utilizes pre-processing, an automatic unloading double cylinder high-pressure diaphragm filtration, and final product automatic ultrafine pulverizing to optimize yield efficiency.

with potential benefits for both manufacturers and consumers.

MATERIALS AND METHODS

Evaluation of the Effect of the Temperature and Time of the Blanch for Cabbage Juice Sensory Quality

To assess the impact of blanching conditions on the sensory attributes of cabbage juice, fresh *Brassica oleracea* (grown in North Carolina) was weighed (10 kg) using a precision laboratory scale and thoroughly washed. The cabbage was then shredded and immersed in a preheated water bath (WB-400, Cole-Parmer) containing 10 L of water at a controlled temperature. Once the water temperature stabilized at the setpoint, the blanching process was initiated. Samples of 2 kg each were removed at 4, 6, 8, 10, and 12 minutes to analyze the effects of blanching duration.

After blanching, the samples were finely pulverized using a Professional XL Food Processor (SharkNinja, NF70). The cabbage was first subjected to slow-speed processing for one minute, followed by two cycles of high-speed pulverization, ensuring uniform texture. Any material adhering to the inner walls was periodically scraped down to maintain homogeneity.

The processed cabbage puree was then subjected to pressing filtration using a modified hydraulic fruit press (Mosakar M5.28GALFP-HJ) equipped with a pressure gauge-controlled bottle jack (Zinko ZNP-20P). The pressure was gradually increased to 0.972MPa, and then maintained until 1200 mL of cabbage juice was extracted. Finally, the sensory properties of the juice were evaluated by a trained panel.

The above experiment was repeated with the preset temperatures being 50° C, 60° C, 70° C, 80° C, and 90° C. The experiments at each temperature were repeated three times.

Evaluation of the Effect of the Pressure and Duration Time of the Pressing Filtration on the Dietary Fiber Content of Cabbage Filter Cake

To determine the optimal pressure and duration for pressing filtration, 10 kg of fresh cabbage was weighed, washed, shredded, and subjected to blanching at 80 °C for 10 minutes, based on the previously optimized conditions. The blanched cabbage was then pulverized in batches of 2000 g per trial, ensuring uniform consistency.

A portion (100 g) of the resulting filter cake was reserved for dietary fiber content analysis, while the remaining material was transferred into a reinforced hydraulic filter press equipped with a pressure gauge-controlled bottle jack. The applied pressure was incrementally increased to preset force levels corresponding to 5–9 tons. The filtration process was maintained for 30, 60, 90, 120, and 150 minutes to assess the effect of duration on fiber retention. At each time point, 100g samples of the filter cake were collected and analyzed for TDF, IDF, and SDF.

After removal, the filter bag was tied tightly and the Fruit Press was reassembled. The jack was adjusted to quickly restore the original pressure, and pressing filtration was continued until the final sampling point. Pressing forces of 5, 6, 7, 8, and 9 tons were applied in separate trials to repeat the experiment, with each condition performed in triplicate. Since the diameter of the Fruit Press plate is 32 cm (yielding an area of 806.8 cm²), the corresponding pressures for pressing forces of 5, 6, 7, 8, and 9 tons were calculated using the equation:

$$Pressure\ (Pa) = \frac{Force\ (N)}{Area\ (m^2)}$$

Here, 1 metric ton = 9,806 N, and 806.8 cm² = 0.08068 m². Applying this formula, the resulting pressures were:

0.608 MPa (5 tons), 0.729 MPa (6 tons), 0.851 MPa (7 tons), 0.972 MPa (8 tons), and 1.09 MPa (9 tons).

Dietary Fiber Analysis

The Association of Official Analytical Collaboration (AOAC) Official Method 991.43 (Total, Soluble, and Insoluble Dietary Fiber in Foods) was applied to quantify TDF, IDF, and SDF in cabbage filter cake samples (25). This widely accepted standardized method involves enzymatic digestion using α-amylase, protease, and amyloglucosidase to simulate gastrointestinal conditions, followed by gravimetric determination of fiber residues (25).

Evaluation of the Effect of Cabbage Powder Addition Ratios on the Taste and Flavor of the Buns and Beef Patties of Hamburger

To evaluate the effect of cabbage powder addition on the sensory attributes of hamburger components, cabbage filter cake was first dried at 60 °C for 12 hours in a hot-air oven and then milled into powder using a high-speed food processor (Model X2000, 30,000 rpm) to achieve a particle size of approximately 150 µm. The resulting cabbage powder

https://doi.org/10.59720/25-061

was incorporated into buns and beef patties at varying concentrations.

For the buns, 1 kg of flour, 21.5 g of instant yeast, 475 g of water, and a predetermined amount of cabbage powder were combined and thoroughly kneaded to achieve a uniform dough. The dough was allowed to ferment for 2 hours, followed by additional shaping into 10 individual buns, which underwent a secondary fermentation for 1 hour. The buns were then baked at 190 °C for 18 minutes using a conventional electric oven and subsequently assessed for taste and texture.

Similarly, beef patties were prepared by blending 1 kg of ground beef with different concentrations of cabbage powder. The mixture was formed into patties and grilled on a preheated electric grill set to 180 °C until the internal temperature of each patty reached 70 °C, ensuring proper doneness before undergoing sensory evaluation.

To systematically assess the impact of cabbage powder incorporation, six levels of addition (0 g, 100 g, 200 g, 300 g, 400 g, and 500 g) were tested following the experimental procedures described above. Each formulation was prepared and evaluated in triplicate.

Sensory Evaluations

Sensory evaluation was performed by a panel of 15 volunteers (8 women, 7 men, aged 18-30 years). The evaluation of cabbage juice involved the presentation of 100 mL of each sample in transparent glass cups at room temperature (25 ± 2°C). To ensure unbiased assessment, samples were randomly coded with three-digit numbers and presented in a randomized order. Panelists were instructed to cleanse their palates between samples by rinsing with water. Although the panel demographic was limited to young adults (18–30 years), this group represents a key segment of the target consumer base for fast food and convenience products such as hamburgers. Nonetheless, the relatively narrow age range may introduce bias, and future studies should consider broader demographic representation to validate sensory findings.

Panelists were informed about the nature of the study but were not aware of the specific treatment parameters for the samples. A training session was conducted prior to evaluation, during which panelists were introduced to the descriptor definitions and practiced using the scale with reference samples to ensure consistent interpretation.

Panelists assessed each sample using a 100-point palatability scale with clearly defined criteria:

81–100: Sweet and refreshing; highly palatable
61–80: Neutral (neither sweet nor spicy); moderately palatable
41–60: Noticeably spicy; mildly palatable
21–40: Strong spicy notes; poor palatability
0–20: Excessively spicy; very poor palatability

For the evaluation of the buns and beef patties, the same panel conducted assessments in separate sessions, following identical procedures. Each session included a control sample (zero-addition, without cabbage powder) for comparison. Bun and beef patty samples, prepared according to the previously described method, were served on white ceramic plates at room temperature (25 ± 2 °C). All samples, including the control, were coded with random three-digit numbers and presented in a fully randomized order within each session to minimize expectation bias.

Panelists were instructed to rinse their mouths with water and consume a small piece of an unsalted cracker between samples to cleanse their palates. While panelists were informed about the nature of the study, they were not aware of the specific cabbage powder concentrations used in the samples.

To assess sensory attributes, panelists rated each sample on a 100-point scale, assigning up to 50 points for flavor and 50 points for taste, based on the following criteria:

Flavor (vs. zero-addition sample): 41–50 (no flavor change); 31–40 (minor flavor change); 21–30 (medium flavor change); 11–20 (high flavor change); 0–10 (very high flavor change).

Taste (vs. zero-addition sample): 41–50 (No taste change); 31–40 (minor taste change); 21–30 (medium taste change); 11–20 (high taste change); 0–10 (very high taste change).

Our study is approved by the Scientific Review Committee (SCR) of the East Chapel Hill High School for human subject research, it falls under the exemption category described in 45 CFR 46.104(d) of the US Federal Policy for the Protection of Human Subjects (Code of Federal Regulations, 2024), as it involves taste evaluation of wholesome foods without additives (6). All participants provided informed consent prior to participation.

The BET Surface Area and Pore Size Analysis of the Cabbage Powder

To characterize the porosity and surface area of cabbage powder, the material was first processed to ensure uniform particle size. The powder was sieved using an automatic sieve shaker (Vevor, 50W, 1150 beats/min) equipped with a 60-mesh sieve (approximately 250 μm aperture), and any retained particles were further pulverized and re-sieved to maintain consistency. The sieved powder was then dried in a convection oven at 40 °C for 24 hours to eliminate residual moisture before analysis.

The BET surface area and pore size distribution of the dried cabbage powder were determined using a Micromeritics ASAP 2460 analyzer. To remove any adsorbed contaminants, samples were subjected to vacuum degassing at 40 °C for 12 hours, a temperature chosen to avoid thermal degradation of heat-sensitive organic components, in accordance with previous protocols for plant-based materials (24). The analysis was conducted under controlled conditions, utilizing N_2 as the adsorptive gas, with an analysis bath temperature of 77.350 K and an equilibration interval of 3 seconds. The specific surface area was calculated using the BET equation for P/P^0 values between 0.01 and 0.30, while pore volume was determined through the Barrett–Joyner–Halenda (BJH) model.

Statistical Analysis

All experiments were repeated at least three times. The results of the dietary fiber content are presented as mean ± standard deviation (SD) and the results of the sensory evaluation are presented as mean ± 95% confidence interval radius (95% CI). Statistical significance was determined using two-way and one-way ANOVA, with $p < 0.05$ considered significant. Where significant differences were detected, Tukey's Honest Significant Difference test was employed for post hoc comparisons following one-way ANOVA. For two-way ANOVA, Fisher's Least Significant Difference (LSD) multiple comparison procedure and analysis of simple effects were conducted when significant interactions were observed. Statistical analysis was performed using SPSS version 27.0 (IBM Corporation, Armonk, NY). Graphs were generated using Microsoft Excel (Microsoft Corporation, Redmond, WA).

ACKNOWLEDGMENTS

This study was assisted by a sensory evaluation team of 15 volunteers, through whom key sensory evaluation data were obtained.

Received: February 21, 2025
Accepted: July 6, 2025
Published: November 16, 2025

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