NUTRITIONAL AND ANTIOXIDANT PROPERTIES OF SPRAY-DRIED APPLE PEEL POWDER: VALUE-ADDED FOOD INGREDIENT PERSPECTIVE

Throngvid Hongsaprabhas[1,2], Piyawadee Saraphirom[1], Orn-Anong Chiyachet[1], Piyarat Namsena[1], Songklot Phonphuak[3] and Panya Chairattanaphanich[1,4]*

Abstract

The frozen apple processing industry generates substantial by-products, particularly apple peels, which are often discarded as waste. This study developed spray-dried apple peel powder (SDAPP), preserving its nutrients, bioactive compounds, and antioxidant properties. SDAPP, stabilized and stored for six months, underwent a comprehensive analysis of its nutritional composition and antioxidant properties. Nutritional parameters, including ash, moisture, dietary fiber, protein, fat, sugar, and potassium, were analyzed using AOAC validated methods, while B-complex vitamins were quantified using a method adapted from Analytica Chimica Acta standards. Antioxidant activities were assessed using the DPPH free radical scavenging assay (IC_{50}), total phenolic content (TPC), and total flavonoid content (TFC). The results revealed that SDAPP provides 396.39 kcal/100 g and 30 kcal per serving size (8.5 g), with 96.92 g of carbohydrates and 46.55 g of sugar/100 g. Protein and fat contents were low at 0.94 g and 0.55 g/100 g, respectively, with saturated fat accounting for only 0.20 g/100 g.

[1]Faculty of Science and Technology, Rajabhat Maha Sarakham University, Muang District, Maha Sarakham Province 44000

[2]Sahapan Century Co., Ltd. Lak Si District, Bangkok 10210

[3]Faculty of Management Sciences, Surindra Rajabhat University, Mueang District, Surin Province 32000

[4]Greendeli Foods Co., Ltd. Khlong Luang District, Pathum Thani Province 12120

*corresponding author e-mail: panya.ch@rmu.ac.th

Received: 30 January 2025; Revised: 25 April 2025; Accepted: 25 April 2025

DOI: https://doi.org/10.14456/lsej.2025.1

SDAPP had a high potassium content of 269.70 mg/100 g and a low sodium content of 12.96 mg/100 g. The antioxidant activity showed the DPPH scavenging activity of 0.61 mg Trolox/g dry weight with the IC_{50} value of 63.141 μg/ml. The TPC and TFC were 5.351 mg GAE/100 g and 7.26 mg QE/100 g, respectively. These findings highlight SDAPP's nutritional and antioxidant potential, positioning it as a promising ingredient for functional food and beverage applications tailored to health-conscious and antioxidant-seeking consumers.

Keywords: apple peel, spray-dried powder, nutritional composition, antioxidants

Introduction

Apple peels are a by-product of the apple processing industry, such as apple juice, dried apples, and jam production. Apple peels are generally considered waste or used in the animal feed industry. However, recent studies have found that apple peels contain important nutritional and bioactive compounds that are beneficial to health, such as antioxidants, dietary fiber, and vitamins (Murakonda & Dwivedi, 2021; de Sena Andrade et al., 2023). Reusing apple peels not only reduces waste in the production process, but also adds value to existing raw materials and can meet the circular economy concept, which reduces environmental impacts and creates new opportunities in the health food market (Costa et al., 2022; Rashid et al., 2023).

Previous studies have shown that apple peels are a rich source of many health-promoting nutrients, including polyphenols, dietary fiber, vitamins and minerals, flavonoids, and phenolic compounds (Lyu et al., 2020). In particular, polyphenols, which have antioxidant properties, can help reduce the risk of chronic diseases such as cardiovascular disease, cancer, and diabetes (Shehzadi et al., 2020; Oyenihi et al., 2022). Examples of essential compounds in this group include quercetin and anthocyanins. In addition, flavonoids and phenolic compounds play an important role in fighting inflammation, promoting blood vessel health, and protecting cells from damage caused by free radicals (Qadri et al., 2022).

The growing consumer awareness of health and sustainability has significantly driven the market for dietary supplements and health foods made from natural ingredients (Djaoudene et al., 2023). Apple peels, a by-product of apple processing industries such as juice or jam production, have emerged as a valuable raw material due to their rich polyphenols, vitamins, dietary fiber, and phenolic compounds (Lyu et al., 2020). Utilizing such by-products not only helps reduce food waste but also supports the principles of the circular economy by transforming waste into functional and sustainable products (Lam et al., 2022).

Spray-dried apple peel powder (SDAPP) is a promising natural alternative to synthetic food additives, offering both nutritional and environmental benefits (Jafari et al., 2023; Comunian et al., 2021). Its development into dietary supplements or functional foods adds value to an otherwise discarded material, while improving resource efficiency in the food production chain. With increasing demand for products containing antioxidants, fiber, and naturally derived compounds, SDAPP is well-positioned to meet the needs of health-conscious consumers, including the elderly and those seeking chemical-free alternatives.

Given the global trend toward clean-label and plant-based products, SDAPP and similar apple peel-derived ingredients hold strong potential for expansion into international markets, particularly in regions where functional foods and health supplements are highly popular (Lyu et al., 2020; Comunian et al., 2021; Jafari et al., 2023). The apple processing industry generates a substantial amount of by-products, including peels, cores, and seeds, which often contribute to environmental challenges. For instance, during peak production periods, a single processing plant can produce up to 2,000–5,000 kilograms of apple peel waste per day. Such large volumes of waste not only increase disposal costs but also pose environmental concerns due to improper waste management, such as methane emissions from decomposition in landfills. Addressing this issue by valorizing apple by-products, particularly peels rich in bioactive compounds, aligns with the principles of sustainable development and circular economy, enabling the transformation of waste into value-added products (Green Deli Foods Co., Ltd., personal communication, 2024).

To address this issue, developing apple peel juice into spray-dried powder offers a sustainable solution that reduces waste and transforms by-products into valuable raw materials for health food products, such as drink powders, food additives, or ingredients for the dietary supplement industry. Consequently, this research focused on the development of apple peel juice into spray-dried powder, aiming to minimize waste in the production process while adding value to previously overlooked apple peels. The study also analyzed the nutritional value and antioxidant properties of the resulting powder, along with strategies for creating marketing opportunities within the increasingly popular health product sector.

Methodology

1. Apple peel and spray-dried apple peel powder (SDAPP) preparation

Fresh apple peels sourced from a frozen apple processing plant (Greendeli Foods Co., Ltd., Thailand) were stored at 4 °C to preserve their freshness prior to processing. The apple peels were then subjected to an extraction process to separate the pulp, which was subsequently used as the base material for producing spray-dried apple peel powder. The spray-drying process was conducted using a pilot-scale spray dryer (Euro Best Technology Co., Ltd., Thailand) with the following operating parameters: an inlet temperature of 160 ± 2 °C, an outlet temperature of 80 ± 5 °C, a feed flow rate of 250 ml/h, and a nozzle diameter of 0.7 mm. The atomization was performed under compressed air at 2.0 bar. These conditions were optimized to ensure rapid drying while preserving the antioxidant and nutritional properties of the extract, as supported by previous studies on fruit-based powders (Jafari et al., 2023; Qadri et al., 2022).

The detailed preparation steps for producing spray-dried apple peel powder (SDAPP) are illustrated in Figure 1 and can be summarized as follows. First, fresh apple peels are collected as by-products from the frozen apple processing line, where large quantities of peel waste are generated during trimming and cutting. These peels are then carefully sorted to remove any foreign materials or damaged portions and subsequently stored at 4 °C to preserve their freshness and prevent microbial or enzymatic degradation before processing. Next, the cleaned peels are blended into a uniform pulp to facilitate juice extraction. The resulting apple peel juice, which contains both soluble nutrients and bioactive compounds, is then mixed with 20% (w/w) maltodextrin, which acts as a drying aid to enhance powder formation, prevent stickiness, and improve flowability. This mixture is subsequently fed into a spray dryer, where it is atomized into a fine mist through a high-pressure nozzle. The atomized droplets are rapidly exposed to a high-temperature drying chamber, causing immediate evaporation of moisture and forming a fine, dry powder. This process effectively retains the nutritional and antioxidant properties of the original peel extract while yielding a shelf-stable, functional ingredient suitable for use in food and health-related products.

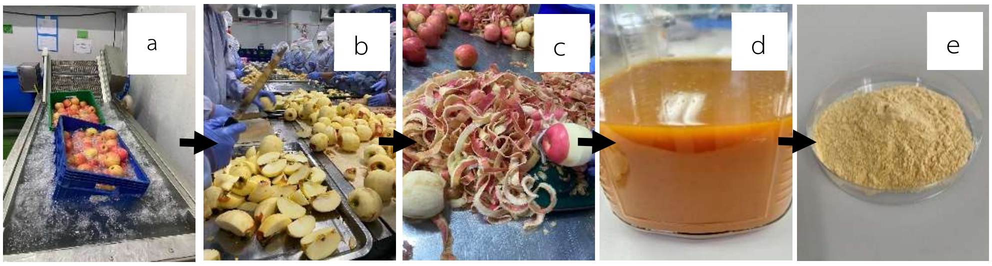

Figure 1 The preparation steps for producing SDAPP using the spray drying process (a-b) Frozen apple processing (c) Fresh apple peel (d) Apple peels juice extract (e) SDAPP.

2. Analysis of nutritional composition in spray-dried apple peel powder (SDAPP)

The analysis of apple peel powder was conducted following standard methods to ensure the accuracy and reliability of the results. Nutritional composition in SDAPP was determined using methods validated by the Association of Official Analytical Chemists (AOAC). Moisture content was analyzed using AOAC (2023) method 930.04, while ash content followed AOAC (2023) method 900.02. Dietary fiber was assessed using the AOAC (2023) method 985.29. Additionally, the analysis of sugars adhered to the compendium of methods for food analysis (2003). Specific in-house methods were also employed to measure components such as saturated and total fat, ensuring compliance with internationally recognized protocols. These methodologies provide a comprehensive understanding of the nutritional composition of the SDAPP.

The analysis of the sample was conducted by Central Laboratory (Thailand) Co., Ltd., using internationally recognized methods. The sodium content was determined based on AOAC guidelines, while the analysis of vitamin A (β-carotene) followed the methodology outlined in the chemical and technical assessment (2004). The B-complex vitamins, including B1 (thiamine), B2 (riboflavin), B3 (niacinamide), B5 (pantothenic acid), and B6 (pyridoxine), were analyzed using an in-house method developed from Analytica Chimica Acta standards. All analyses were performed with a focus on precision and accuracy, adhering to ISO/IEC 17025 standards to ensure reliable and consistent results.

3. Analysis of antioxidant activity in spray-dried apple peel powder (SDAPP)

3.1 Preparation of solutions for antioxidant activity analysis (adapted from Zhu et al., 2011)

For antioxidant activity analysis, a 60 μM 2,2-diphenyl-1-picrylhydrazyl (DPPH) solution was prepared by accurately weighing 0.0024 g of DPPH and dissolving it in methanol, followed by adjusting the volume to 100 ml using a volumetric flask. A Trolox standard stock solution (1,000 mg/l) was prepared by weighing 0.01 g of Trolox, dissolving it in methanol, and adjusting the volume to 10 ml in a volumetric flask. A series of Trolox standard solutions with concentrations of 200, 150, 100, and 50 mg/l were then prepared by pipetting 2.00, 1.50, 1.00, and 0.50 ml, respectively, of the Trolox stock solution into separate 10 ml volumetric flasks and diluting each to volume with methanol. The SDAPP sample solution (1,000 mg/l) was prepared by dissolving 1 mg of SDAPP in 1 ml of methanol and transferring the solution to a microcentrifuge tube for storage and subsequent analysis. All solutions, including the prepared 2,2-diphenyl-1-picrylhydrazyl solution, Trolox standards, and the SDAPP sample, should be stored away from light to preserve their stability and prevent degradation.

3.2 Antioxidant activity testing using 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity

The DPPH assay was employed to evaluate the antioxidant activity of the samples. A total of 2.90 ml of the prepared 60 μM DPPH solution was dispensed into a test tube, followed by the addition of 0.10 ml of either a Trolox standard solution or the SDAPP sample. The mixture was allowed to stand in the dark for one hour to avoid light-induced reactions.

After the incubation period, the absorbance of the solution was measured at 517 nm using a spectrophotometer. A standard calibration curve was constructed by plotting the absorbance values of Trolox standard solutions at concentrations of 200, 150, 100, and 50 mg/l against their respective concentrations.

This calibration curve served as a reference to calculate the percentage of DPPH radical scavenging activity (%DPPH inhibition) for the SDAPP sample, providing a quantitative measure of its antioxidant capacity (Zhu et al., 2011). The IC_{50} values were calculated using linear regression analysis to indicate antioxidant capacity.

$$\%\text{DPPH radical scavenging activity} = \left[\frac{(A_{control} - A_{standard/sample})}{A_{control}}\right] \times 100$$

When $A_{control}$ is the absorbance value of DPPH

A is the absorbance value of the standard substance

A_{sample} is the absorbance value of SDAPP

3.3 Total phenolic content analysis (adapted from Bärlocher & Graça, 2020)

To analyze the total phenolic content (TPC) of the sample, 50 µl of a 10 mg/ml sample extract was pipetted into a test tube, followed by the addition of 3 ml of 10% Folin-Ciocalteu reagent. The mixture was thoroughly mixed and allowed to react at room temperature for 15 minutes. Subsequently, 1.5 ml of 10% sodium carbonate (Na_2CO_3) solution was added, and the mixture was again mixed thoroughly. The reaction was then allowed to proceed at room temperature for an additional 15 minutes. After the incubation period, the absorbance of the mixture was measured at 750 nm using a UV-Vis spectrophotometer. The results were expressed as milligrams of gallic acid equivalent per gram of extract (mg GAE/g extract), providing a quantitative measure of the phenolic compounds present in the sample.3.4 Total flavonoid content analysis (adapted from Ghafoor et al., 2019)

To determine the total flavonoid content (TFC) of the sample, 250 µl of a 10 mg/ml sample extract was pipetted into a test tube, followed by the addition of 1.25 ml of distilled water and thorough mixing. Then, 75 µl of 5% sodium nitrite ($NaNO_2$) solution was added, and the mixture was shaken and left at room temperature for 5 minutes. Next, 150 µl of 10% aluminum chloride ($AlCl_3$) solution was added, followed by shaking and incubation at room temperature for 6 minutes. Subsequently, 500 µl of 1 M sodium hydroxide (NaOH) solution and 775 µl of distilled water were added to the test tube. The mixture was shaken to ensure homogeneity, and the absorbance of the final solution was measured at 510 nm using a UV-Vis spectrophotometer. The total flavonoid content was expressed as milligrams of quercetin equivalent (QE), providing a quantitative measure of the flavonoid compounds present in the sample.

All experiments, including antioxidant assays and nutritional analyses, were conducted in triplicate (n = 3) to ensure data reliability and statistical accuracy. Results are presented as mean ± standard deviation (SD). Statistical comparisons were made using one-way ANOVA at a significance level of $p < 0.05$.

The yield of the spray-drying process was calculated based on the ratio of the weight of the final spray-dried apple peel powder (SDAPP) to the total solid content in the feed solution. The average yield obtained under the specified spray-drying conditions was 38.7% ± 1.2%, which is consistent with the typical range reported in the literature for fruit-based extracts (Jafari et al., 2023; Qadri et al., 2022).

Results

The results of the nutritional composition and antioxidant properties of spray-dried apple peel powder (SDAPP) were as follows:

1. Energy and macronutrient composition

The analysis revealed that SDAPP contains approximately 396.39 kcal per 100 g and 30 kcal per serving size (8.5 g), making it suitable for inclusion in dietary supplement products. The product contains a total carbohydrate content of 96.92 g per 100 g, which serves as the primary energy source. It has a sugar content of 46.55 g per 100 g, which should be considered when formulating products for consumers limiting sugar intake. The protein content is relatively low at 0.94 g per 100 g, while the fat content is minimal at 0.55 g per 100 g, with saturated fat accounting for only 0.20 g per 100 g. When analyzing the main components of SDAPP and calculating the nutritional information, it was found that 1 kilogram of packaged product can be divided into 1 tablespoon (8.5 grams), providing 30 kilocalories of energy.

The physicochemical properties and nutritional composition of SDAPP and the comparison of nutritional composition and antioxidant properties between SDAPP and apple pomace powder are shown in Table 1. It is evident that SDAPP exhibits superior antioxidant properties compared to general APP, as reflected by its higher total phenolic content (TPC) and total flavonoid content (TFC). While APP contains more dietary fiber, SDAPP provides higher calories and carbohydrates, making it well-suited for energy supplement products such as health drinks and energy bars. However, the high sugar content of SDAPP presents a challenge, necessitating improvements such as sugar reduction or the incorporation of low glycemic index sweeteners to better accommodate health-conscious consumers. Compared to apple pomace powder (APP), SDAPP offers superior antioxidant properties, with a 20–30% higher TPC and TFC content. This makes SDAPP more suitable for functional food applications targeting antioxidant and anti-aging markets. The analysis showed that SDAPP contains a high potassium content of 269.70 mg per 100 g (equivalent to 1% of the recommended daily intake per serving). This indicates its potential as a dietary potassium source. Meanwhile, the sodium content is low at 12.96 mg per 100 g, making it suitable for developing low-sodium food products for health-conscious consumers.

Table 1 Comparison of nutritional composition and antioxidant properties between SDAPP and apple pomace powder.

Parameters	SDAPP* (per 100 g)	Apple Pomace Powder (APP) (Bhushan et al., 2008; Lyu et al., 2020)
Calories (kcal)	396.39	350-370
Carbohydrate (g)	96.92	80-85
Sugar (g)	46.55	20-30
Dietary Fiber (g)	1.69	15-25
Protein (g)	0.94	4-5
Total Fat (g)	0.55	0.8-1.2
Potassium (mg)	269.70	250-300
Sodium (mg)	12.96	10-20
Total phenolic content (TPC, mg GAE/100 g)	5.351	3-5
Total flavonoid content (TFC, QE/100 g)	7.26	5-6
DPPH radical scavenging activity (mg Trolox/g dry weight)	0.61	0.4-0.6
IC_{50} value (μg/ml)	63.141	~80
Cholesterol (g)	Not detected	
Saturated Fat (g)	0.20	
Moisture (g)	0.44	
Ash (g)	1.15	

Remark *All values are expressed as mean ± SD (n = 3).

2. Vitamin composition

Table 2 highlights the vitamin content of SDAPP, showcasing beneficial levels of B vitamins, including vitamin B1 (thiamine), vitamin B2 (riboflavin), and vitamin B3 (nicotinamide), which contribute to its nutritional value. However, spray drying may lead to a reduction in certain vitamins, particularly vitamin C and other heat-sensitive vitamins. To address this, encapsulation techniques and controlled production conditions can be employed to minimize nutrient loss and preserve the product's nutritional quality. Supporting this, a study on the development of an instant powdered beverage made from carrots, oranges, and lemons revealed that carrot powder produced by spray drying showed a decrease in vitamin C content compared to the fresh raw materials (Wirivutthikorn, 2022).

Table 2 The mineral and vitamin content of SDAPP.

Parameters	The mineral and vitamin content (per 100 grams)*
Vitamin A (B-Carotene)	Not detected
Vitamin B Complex	0.62363 mg
Vitamin B1 (Thiamine)	Not detected
Vitamin B2 (Riboflavin)	0.32290 mg
Vitamin B3 (Nicotinamide)	0.0785 mg
Vitamin B3 (Nicotinic acid)	Not detected
Vitamin B5 (Pantothenic)	0.17460 mg
Vitamin B6 (Pyridoxine)	0.04778
Vitamin B6 (Pyridoxal)	Not detected
Vitamin B7 (Biotin)	Not detected
Vitamin B9 (Folic acid)	Not detected
Vitamin B12 (Cyanocobalamin)	Not detected

Remark *All values are expressed as mean ± SD (n = 3).

3. Antioxidant properties

3.1 DPPH radical scavenging activity

The DPPH assay revealed that SDAPP exhibits a DPPH radical scavenging activity obtained in Table 1. This value reflects the sample's ability to neutralize DPPH radicals (2,2-diphenyl-1-picrylhydrazyl), a standard method for evaluating antioxidant activity. The observed value indicates moderate antioxidant potential compared to Trolox, a standard antioxidant reference.

3.2 IC_{50} (half-maximal inhibitory concentration)

The IC_{50} value of SDAPP represents the concentration required to reduce free radical activity by 50%. A lower IC_{50} value indicates higher antioxidant capacity. The IC_{50} value of SDAPP suggests moderate antioxidant potential but does not reach the level of highly potent antioxidants (e.g., IC_{50} < 10 μg/ml is considered high potency).

3.3 Total phenolic content (TPC)

The total phenolic content of SDAPP detected in this study was expressed as milligrams of gallic acid equivalent (GAE) per 100 g. Phenolic compounds play a crucial role in antioxidant activity by donating hydrogen atoms or scavenging free radicals, thereby reducing cellular damage. The TPC value of 5.351 mg GAE/100 g is considered satisfactory, especially given the correlation between phenolic compounds and antioxidant capacity.

3.4 Total flavonoid content (TFC)

The total flavonoid content of SDAPP was detected as more than 7 mg QE/100 g, expressed as milligrams of quercetin equivalent (QE) per 100 g. Flavonoids are a significant group of antioxidants that protect cells from oxidative stress and enhance immune function. The TFC value obtained indicates good antioxidant potential, with flavonoids complementing the activity of phenolic compounds.

Discussions

1. Transforming fresh fruits into powders: The case of SDAPP

The transformation of fresh fruits into powders, such as spray-dried apple pomace powder (SDAPP), has gained traction in recent years due to its numerous benefits. By reducing the moisture content of the product to less than 6 %, microbial growth and enzymatic activity are inhibited, significantly extending the product's shelf life. This also reduces costs associated with storage, transportation, and packaging. Additionally, utilizing by-products like fruit peels and cores enhances resource efficiency and aligns with the principles of the circular economy. Fruit and vegetable powders retain their natural flavor and nutrients without the need for additives or artificial colors, making them versatile ingredients for various food processing applications (Wolfe and Liu, 2003; Lyu et al., 2020).

SDAPP stands out as a carbohydrate-rich product with high antioxidant content, making it a suitable candidate for use in dietary supplements. It is particularly appealing for applications such as health drinks, powdered beverages, or healthy snack formulations. However, careful consideration is required to manage its sugar content to cater to diabetic or health-conscious consumers. With its combination of nutritional value and antioxidant properties, SDAPP offers excellent potential as a value-added ingredient in the food and health industries. It aligns well with the growing demand for products targeting health-conscious markets (Wolfe et al., 2003; Feng et al., 2021; Zielinska et al., 2019; Arnold and Gramza-Michalowska, 2024).

Despite its potential, certain challenges need to be addressed for the commercial-scale production of SDAPP. Maintaining the stability of bioactive compounds during large-scale spray-drying processes remains a critical issue. Additionally, achieving cost-efficient production at an industrial scale will be key to its market success. A comparative analysis of SDAPP with other powdered products is presented in Table 3, highlighting its strengths and market potential.

The comparative data highlights that both SDAPP and APP benefit from low raw material costs, as they utilize by-products from fruit processing. This approach not only reduces production costs but also aligns with the principles of the circular economy. In contrast, blueberry powder incurs a high raw material cost due to its dependence on seasonal fruits.

Table 3 Comparison table of marketing characteristics involving SDAPP and other products.

Parameter	SDAPP (Wolfe et al., 2003; Veberic et al., 2005)	Apple pomace powder (APP) (Schieber et al., 2001)	Blueberry powder (Kalt et al., 2008)
Raw material cost	Low (by-product)	Low (by-product)	High (seasonal fruit)
Antioxidant content	High (TPC: 5.351 mg GAE/100 g)	Moderate (TPC: 3–5 mg GAE/100 g)	High (TPC: 10–15 mg GAE/100 g)
Market demand	Growing in functional foods	Niche in dietary supplements	Popular in premium health foods
Processing cost	Moderate (spray drying)	Low (simple drying)	High (freeze drying)

In terms of antioxidant capacity, SDAPP demonstrates higher levels (TPC: 5.351 mg GAE/100 g) compared to APP (TPC: 3–5 mg GAE/100 g) but falls short of Blueberry Powder (TPC: 10–15 mg GAE/100 g). This positions SDAPP as a strong candidate for use in dietary supplements and functional food products. SDAPP aligns well with the growing functional foods market, particularly among health-conscious consumers seeking nutritious and sustainable options. While APP caters to a more niche market in dietary supplements, blueberry powder enjoys significant demand within the premium product segment. Despite its cost-efficient raw materials, SDAPP's spray-drying production process is moderately expensive. In comparison, APP relies on a simpler drying method that is more cost-effective, whereas blueberry powder uses a freeze-drying process, which has the highest production cost among the three.

2. SDAPP: potential for development into value-added products from an industrial scale perspective

The design of the SDAPP product data, based on its nutritional value and antioxidant properties, highlights its significant potential for industrial-scale development into value-added products (Figure 2). This data offers valuable insights into the applications of SDAPP as a functional ingredient.

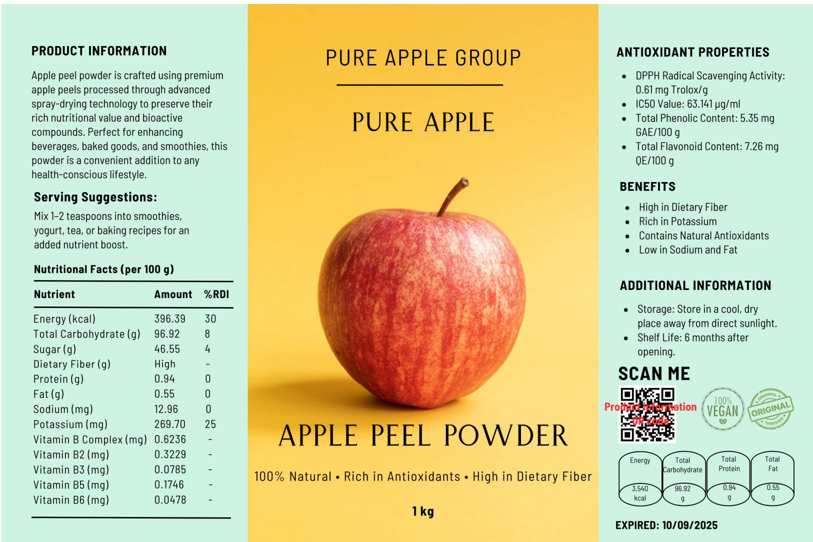

Figure 2 The design of product information.

SDAPP offers several advantages that make it a promising functional ingredient. It provides high nutritional value, delivering 396.39 kcal per 100 g and essential nutrients like potassium (269.70 mg/100 g), which support cardiovascular health. Additionally, SDAPP exhibits moderate antioxidant properties, with a DPPH scavenging value of 0.61 mg Trolox/g, TPC at 5.351 mg GAE/100 g, and TFC at 7.26 mg QE/100 g, making it suitable for functional food applications. From a sustainability perspective, SDAPP promotes a circular economy by valorizing apple peel waste, reducing environmental impact, and adding value to by-products (Lyu et al., 2020).

Despite its potential, there are challenges in commercializing SDAPP. Its high sugar content (46.55 g/100 g) may deter diabetic and health-conscious consumers, necessitating future formulations with low-GI sweeteners. Production costs remain a concern, as the spray-drying process requires advanced equipment and consistent raw materials, leading to higher expenses. Furthermore, consumer education and effective marketing strategies are critical to achieving international market acceptance (Smith et al., 2020).

Looking forward, SDAPP has various applications in health-conscious products such as snacks, powdered drinks, and energy bars. Its antioxidant properties make it suitable for functional teas and skincare supplements, while its high energy content supports sports drinks and recovery products, especially when combined with protein or electrolytes (Guiné et al., 2021). To enhance its commercial viability, future research should focus on reducing sugar content or incorporating additional bioactive compounds to improve health benefits. Stability studies under different storage conditions and consumer acceptance tests across diverse demographics are essential to understand market demand (Lee et al., 2024).

From a commercial perspective, SDAPP targets health-conscious consumers, particularly the elderly and those seeking chronic disease prevention, aligning with the growing demand for functional foods and beverages. Although it leverages low-cost apple peel by-products, high spray-drying costs present a challenge, necessitating cost optimization strategies. Future formulations should focus on reducing sugar content or incorporating low-GI sweeteners to broaden consumer appeal. Despite these challenges, SDAPP's combination of nutritional benefits, sustainability, and versatility positions it as a valuable functional ingredient with significant market potential (Hilton, 2017).

Conclusions

Spray-Dried Apple Peel Powder (SDAPP) demonstrates considerable potential as a functional ingredient due to its rich nutritional composition and antioxidant properties. The product, derived from by-products of the apple processing industry, aligns with the growing emphasis on sustainability and waste valorization in food production. SDAPP is a high-energy product, offering 396.39 kcal per 100 grams, and is particularly notable for its carbohydrate content (96.92 g/100 g), making it a suitable candidate for energy-focused applications. Additionally, its high potassium content (269.70 mg/100 g) and low fat and sodium levels further enhance its appeal to health-conscious consumers. The presence of B vitamins, including B2 and B3, adds to its nutritional profile, contributing to its functional value.

The antioxidant properties of SDAPP underscore its potential as a health-promoting ingredient. The moderate DPPH radical scavenging activity, along with measurable levels of total phenolic and flavonoid content, indicates its efficacy in reducing oxidative stress. These properties position SDAPP as a promising component for anti-aging and cardiovascular health products, catering to the increasing demand for functional foods and beverages targeting wellness and longevity.

With its unique combination of nutritional and bioactive benefits, SDAPP can be developed into various value-added products, including functional beverages, sports nutrition, and health snacks. Its high carbohydrate content makes it suitable for energy bars and recovery products, while its antioxidant properties align with consumer preferences for natural and health-enhancing ingredients. Future product development efforts could focus on addressing its relatively high sugar content through innovative formulations, such as reduced-sugar variants or the incorporation of alternative sweeteners, to broaden its market appeal. Overall, SDAPP offers significant potential for sustainable product innovation, transforming agricultural waste into high-value, health-oriented applications.

Acknowledgement

The authors express their gratitude to Greendeli Foods Co., Ltd. and Sahapan Century Co., Ltd. for their financial support and access to equipment and laboratory resources. We also thank the Faculty of Science and Technology, Rajabhat Maha

Sarakham University, and the Bachelor of Science Program in Biotechnology for their guidance and support in implementing the Cooperative and Work Integrated Education (CWIE) program.

Reference

Arnold M, Gramza-Michalowska A. Recent development on the chemical composition and phenolic extraction methods of apple (Malus domestica)—a review. Food and Bioprocess Technology 2024;17(9):2519-2560.

Association of Official Analytical Chemists (AOAC). Official Method 930.04: Moisture in Foods. AOAC International; 2023.

Association of Official Analytical Chemists (AOAC). Official Method 900.02: Ash in Foods. AOAC International; 2023.

Association of Official Analytical Chemists (AOAC). Official Method 985.29: Total Dietary Fiber in Foods. AOAC International; 2023.

Association of Official Analytical Chemists (AOAC). Official Methods for Sodium Determination. AOAC International; 2023.

Bärlocher F, Graça MA. Total phenolics. Methods to study litter decomposition: a practical guide 2020:157-161.

Comunian TA, Silva MP, Souza CJ. The use of food by-products as a novel for functional foods: Their use as ingredients and for the encapsulation process. Trends in Food Science & Technology 2021;108:269-280.

Costa JM, Ampese LC, Ziero HDD, Sganzerla WG, Forster-Carneiro T. Apple pomace biorefinery: Integrated approaches for the production of bioenergy, biochemicals, and value-added products–An updated review. Journal of Environmental Chemical Engineering 2022;10(5):108358.

de Sena Andrade RAM, da Silva DC, de Souza MMB, et al. Microencapsulation of phenolic compounds from cashew apple (Anacardium occidentale L.) agro-food waste: Physicochemical characterization, antioxidant activity, biodisponibility and stability. Food Chemistry Advances 2023;3:100364.

Djaoudene O, Romano A, Bradai YD, et al. A global overview of dietary supplements: Regulation, market trends, usage during the COVID-19 pandemic, and health effects. Nutrients 2023;15(15):3320.

Feng S, Yi J, Li X, Wu X, Zhao Y, Ma Y, Bi J. Systematic review of phenolic compounds in apple fruits: Compositions, distribution, absorption, metabolism, and processing stability. Journal of agricultural and food chemistry 2021;69(1):7-27.

Ghafoor K, Ahmed IAM, Doğu S, Uslu N, Fadimu GJ, Al Juhaimi F, Özcan MM. The effect of heating temperature on total phenolic content, antioxidant activity, and phenolic compounds of plum and mahaleb fruits. International Journal of Food Engineering 2019;15(11-12):20170302.

Guiné RP, Barroca MJ, Coldea TE, Bartkiene E, Anjos O. Apple fermented products: An overview of technology, properties and health effects. Processes 2021;9(2):223.

Gupta A, Sanwal N, Bareen MA, et al. Trends in functional beverages: Functional ingredients, processing technologies, stability, health benefits, and consumer perspective. Food Research International 2023;170:113046.

In-house Methods Based on AOAC Standards. Saturated and total fat analysis. Internationally Validated Protocols; 2023.

ISO/IEC 17025. General Requirements for the Competence of Testing and Calibration Laboratories. International Organization for Standardization; 2017.

Jafari S, Jafari SM, Ebrahimi M, Kijpatanasilp I, Assatarakul K. A decade overview and prospect of spray drying encapsulation of bioactives from fruit products: Characterization, food application, and in vitro gastrointestinal digestion. Food Hydrocolloids 2023;134:108068.

Kalt W, Blumberg JB, McDonald JE, Vinqvist-Tymchuk MR, Fillmore SA, Graf BA, et al. Identification of anthocyanins in the liver, eye, and brain of blueberry-fed pigs. Journal of agricultural and food chemistry 2008;56(3):705-712.

Kang YG, Kwon J, Kwon S, Kim AR. Synergistic effects of Korean mistletoe and apple peel extracts on muscle strength and endurance. Nutrients 2024;16(19):3255.

Lam M, Khoshkhat P, Chamani M, et al. In-depth multidisciplinary review of the usage, manufacturing, regulations, & market of dietary supplements. Journal of Drug Delivery Science and Technology 2022;67:102985.

Lee JH, Kim MJ, Kim, CY. The development of new functional foods and ingredients. Foods 2024;13(19):3038.

Li W, Yang R, Ying D, Yu J, Sanguansri L, Augustin MA. Analysis of polyphenols in apple pomace: A comparative study of different extraction and hydrolysis procedures. Industrial Crops and Products 2020;147:112250.

Lyu F, Luiz SF, Azeredo DRP, Cruz AG, Ajlouni S, Ranadheera CS. Apple pomace as a functional and healthy ingredient in food products: A review. Processes 2020;8(3):319.

Lyu, F, Luiz SF, Azeredo DRP, Cruz AG, Ajlouni S, Ranadheera CS. Apple pomace as a functional and healthy ingredient in food products: A review. Processes 2020;8(3):319.

Mohammadi N. Recovery, chemical, and bioactivity characterisation of polyphenols from fruits and by-products in food applications: A circular solution toward resilient food systems [doctoral dissertation]. University of Limerick; 2024.

Murakonda S, Dwivedi M. Powders from fruit waste. Food powders properties and characterization. 2021:155-168.

Oyenihi AB, Belay ZA, Mditshwa A, Caleb OJ. "An apple a day keeps the doctor away": The potentials of apple bioactive constituents for chronic disease prevention. Journal of Food Science 2022;87(6):2291-2309.

Qadri T, Naik HR, Hussain SZ, et al. Comparative evaluation of apple juice concentrate and spray dried apple powder for nutritional, antioxidant and rheological behaviour. Quality Assurance and Safety of Crops & Foods 2022;14(2):74-85.

Qadri T, Naik HR, Hussain SZ, et al. Spray dried apple powder: Qualitative, rheological, structural characterization and its sorption isotherm. LWT - Food Science and Technology 2022;165:113694.

Rashid R, Wani SM, Manzoor S, Masoodi FA, Dar MM. Green extraction of bioactive compounds from apple pomace by ultrasound assisted natural deep eutectic solvent extraction: Optimisation, comparison and bioactivity. Food Chemistry 2023;398:133871.

Schieber A, Keller P, Carle R. Determination of phenolic acids and flavonoids of apple and pear by high-performance liquid chromatography. Journal of Chromatography A 2001;910(2):265-273.

Shehzadi K, Rubab Q, Asad L, Ishfaq M, Shafique B, Ali Nawaz Ranjha MM, Sabtain B. A critical review on presence of polyphenols in commercial varieties of apple peel, their extraction and Health benefits. Open Access Journal of Biological Science Research 2020;6:18.

Wirivutthikorn W. Processing development of instant juice powder product from carrot orange and lemon by using foam mat drying. Burapha Science Journal 2022;48-65.

Wolfe K, Wu X, Liu RH. Antioxidant activity of apple peels. Journal of Agricultural and Food Chemistry 2003;51(3):609-614.

Wolfe KL, Liu RH. Apple peels as a value-added food ingredient. Journal of Agricultural and Food Chemistry 2003;51(6):1676-1683.

Zhu KX, Lian CX, Guo XN, Peng W, Zhou H-M. Antioxidant activities and total phenolic contents of various extracts from defatted wheat germ. Food Chemistry 2011;126(3):1122-1126.

Zielinska D, Laparra-Llopis JM, Zielinski H, Szawara-Nowak D, Giménez-Bastida JA. Role of apple phytochemicals, phloretin and phloridzin, in modulating processes related to intestinal inflammation. Nutrients 2019;11(5):1173.