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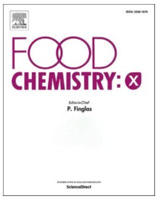

Physicochemical characterization of a composite flour: Blending purple sweet potato and rice flours

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ABSTRACT

In this study, the physicochemical characterization of different ratios of purple sweet potato flour (PSPF) and rice flour was investigated to improve the nutritional value and enrich the variety of rice-based staple food. The results showed that adding PSPF increased total dietary fiber and anthocyanin content whereas decreased amylose content of the composite flours. Additionally, the composite flours exhibited lower thermodynamic parameters and displayed darker, redder, and bluer colors. There were no noticeable changes in the functional group structure of the composite flours. The addition of PSPF decreased the crystallinity and water-holding capacity of the composite flours, whereas increased the average particle size and iodine blue value. PSPF increased the pasting temperature of the flours whereas decreased the breakdown and setback values. Overall, the addition of PSPF significantly affects the nutrition, color and physicochemical properties of the composite flours.

1. Introduction

Rice is the primary grain crop in China. It is traditionally prepared by steaming or cooking to yield rice porridge, cakes, noodles and other products. However, with the advancement of rice processing technology and increasing consumption level, there is an increasing demand for the nutrition and variety of rice products. Current rice-based staple foods, such as rice vermicelli, noodles, and instant rice, often share similar compositions, necessitating the development of innovative products catering to specific nutritional, convenience, and taste preferences. Reports suggest that rice nutrition may be unbalanced, necessitating the addition of nutritional supplements or blending with other ingredients to enhance its nutritional profile and physicochemical properties. (Acharya, Karki, Rai, & Sangroula, 2023; Junaid-ur-Rahman et al., 2022; Zheng et al., 2020).There is a need to accelerate the development of rice products to improve the overall quality of traditional rice foods.

Purple sweet potato (*Ipomoea batatas*) is a special kind of sweet potato that not only contains the nutrients such as starch, dietary fiber, protein and microelements of a regular sweet potato, but is also rich in anthocyanins, a group of flavonoids with a benzopyran structure (Wang, Nie, & Zhu, 2016). Reports have shown that anthocyanins contribute to various health effects, such as antioxidative, antiobesity, immunomodulatory, antiaging, antihyperglycemic, hepatoprotective, antimicrobial and cardiovascular effects (Jokioja et al., 2020). With the increase in healthcare awareness among people, the nutritional value of purple sweet potato has become well-known, and it is now being used in various industries. Some cultivars in Japan have been utilized in a variety of processed commercial products, such as natural food colorants, bread, noodles, juices, confectionary and fermented beverages (Steed & Truong, 2008).Purple sweet potato could be used to enhance food products through color, flavor, sweetness and nutrient (Ahmed, Akter, & Eun, 2010). Due to its high anthocyanin content, purple sweet potato is typically prepared as purple sweet potato flour (PSPF), which serves as a substitute for cereal flours to prompting enhanced nutritional qualities and aesthetic attributes in various products. PSPF is easy to preservation, convenient to use and wide to application, and is now used in different fields, such as baby food, pasta products, and fried food.

Blending, a process that combines two or more ingredients to yield a homogeneous product, is employed to boost functional properties and nutritional value in the food industry. For instance, Chinese steamed bread incorporating PSPF has exhibited enhanced color, polyphenol content, and antioxidant activity (Cui & Zhu, 2022) Other studies have

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shown that PSPF can improve the structural properties of extruded rice products (Wang et al., 2021). The extruded breakfast cereals made from whole red rice, corn flour, and PSPF possess superior cell structures with smoother and thinner cell walls compared to non-optimized samples (Senevirathna, Ramli, Azman, & Juhari, 2023) Furthermore, incorporating 20% PSPF into refined wheat flour for noodles has been found acceptable to consumers, while also enriching their nutritional profile (Uthai, Suktanarak, Chetyakamin, & Thumrongchote, 2022) Collectively, these findings underline the beneficial impacts of PSPF on product quality.

The physicochemical properties of food raw materials play a pivotal role in determining the processing characteristics of the final products. The distinct structures, compositions, and forms of PSPF and rice flour are expected to influence the processing performance of composite flours. The addition of PSPF to rice flour is likely to affect its physicochemical properties in various aspects. However, while most studies have focused on the effects of PSPF on wheat flour products (Hu, Zhou, Zhang, Zhou, & Zhang, 2023; Li et al., 2020; Shan, Zhu, Peng, & Zhou, 2013; Uthai et al., 2022), there is a dearth of research examining the raw material properties of composite flours derived from PSPF and rice flour.

The combination of PSPF and rice flour has the potential to yield a variety of rice-based products, including noodles, vermicelli, steamed bread, bread, and cake. Each product has distinct properties and requires specific raw materials. By blending PSPF with rice flour in different ratios, it is possible to create purple sweet potato and rice products that offer enhanced nutritional value and acceptable sensory qualities. Therefore, it is imperative to investigate the characteristics of composite flours made from PSPF and rice flour. This study explores the nutritional composition and physicochemical properties of composite flours produced by blending PSPF with rice flour in varying proportions. The main purpose is to establish a theoretical foundation for the efficient utilization of purple sweet potato and the development of purple sweet potato-rice staple food products.

2. Materials and methods

2.1. Materials

PSPF and rice were purchased from Shandong Shengdi Sweet Potato Industry Co., Ltd. (Shandong, China) and Yihai Kerry Cereals, Oils, and Foodstuffs Co., Ltd. (Jiangxi, China), respectively. The Straight-Chain Starch Kit was obtained from Megazyme Reagent Co. Ltd. (Ireland). All other reagents used in the study were of analytical grade and obtained from Sinopharm Chemical Reagent Co. (Shanghai, China).

2.2. Composite flour preparation

PSPF underwent sieving through a 100-mesh screen. Raw rice was milled into flour using a cyclone grinder (JXFM110, Shanghai, China) and similarly passed through a 100-mesh sieve. Subsequently, these two raw material powders (500 g) were combined in varying mass ratios from 0:10 to 10:0 and sieved through the 100-mesh screen thrice to ensure adequate dispersion. The resulting composite flour was then homogenized for 30 min in a powder mixing machine (BF-V, Saixin, Jinan, China) to achieve a uniform distribution.

2.3. Nutritional composition analysis

The moisture, fat, total protein, ash, total dietary fiber, and amylose contents of the samples were analyzed using the official methods outlined by the Association of Official Analytical Chemists (AOAC) in 2000. Starch content was determined using the Megazyme Starch Kit (Micro Wise, Beijing, China) following a specific protocol detailed in the kit manual.

In this method, duplicate samples of 100 mg each (with one serving as a sample blank) were combined with 10 mL of 100 mM sodium acetate buffer (pH 5.0) containing 5 mM $CaCl_2$. To the sample tube, 0.1 mL of alpha-amylase was added, while the sample blank tube received 0.1 mL of sodium acetate buffer. The tubes were then subjected to a boiling water bath for 15 min, followed by equilibration at 50 °C for over 5 min in a water bath. Subsequently, the sample tube was supplemented with 0.1 mL of undiluted amyloglucosidase, while the sample blank tube received 0.1 mL of sodium acetate buffer. The tubes were then incubated at 50 °C for 30 min, cooled to room temperature for $>$10 min, and centrifuged at 13,000 rpm for 5 min.

Following centrifugation, a 1.0 mL aliquot of the supernatant was transferred to a tube containing 4 mL of sodium acetate buffer. To this solution, 0.1 mL of the sample or blank sample solution was added, along with 3.0 mL of glucose oxidase and peroxidase reagent. The mixture was incubated at 50 °C for 20 min, and the absorbance value was measured at 510 nm relative to the reagent blank. Additionally, a glucose control test was conducted to ensure accuracy and consistency of the results.

2.4. Fourier transforms infrared spectroscopy

Utilizing Fourier Transforms Infrared Spectroscopy (FTIR), sensitive detections of molecular-level structural alterations in starch were achieved with respect to short-range order. The FTIR spectra were obtained using a Fourier Transform Infrared Spectrometer from Perkin Elmer Instruments (Massachusetts, USA), as detailed by Wang et al. (2023). Thin tablets were prepared by blending 2 mg of the sample with 200 mg of KBr. Spectral recordings were captured within a range of 4000 to 400 cm^{-1} at a speed of 2 cm^{-1}.

2.5. Thermal properties

To assess the thermal properties of both raw materials and composite flours, a Differential Scanning Calorimeter (DSC; Q2000, TA Instruments, Delaware, USA) was employed. This approach was adapted from existing literature research methods, particularly the method described by Mu, Zhang, Raad, Sun, and Wang (2015), with minor modifications. Each sample (3 mg) was mixed with 9 μL of deionized water and encapsulated in an aluminum pan. The pan was then equilibrated at 25 °C for 12h before being heated from 20 °C to 100 °C at a rate of 5 °C/min. Key gelatinization parameters, including onset temperature (To), peak temperature (Tp), conclusion temperature (Tc), and gelatinization enthalpy (ΔH), were recorded.

2.6. Pasting properties

To evaluate the pasting properties of the samples, a Rapid Viscosity Analyzer (RVA; RVA-Super, Perten Instruments, Sweden) was utilized, following the protocol described by Shan et al. (2013). The sample was suspended in distilled water and transferred to an aluminum canister, which was then stirred using a plastic paddle. The suspension was initially held at 50 °C for 1.0 min, heated to 95 °C at a rate of 12 °C/min, maintained at 95 °C for 2.5 min, cooled back to 50 °C at 12 °C/min, and finally held at 50 °C for another 1.0 min. The viscosities were expressed in rapid viscosity units (cP).

2.7. X-ray diffraction (XRD)

X-ray diffraction tests were conducted to analyze the formation of crystalline structures in the composite flour samples. Utilizing an X-ray diffractometer (Rigaku SmartLab SE, Tokyo, Japan) operating at 40 kV and 40 mA with Ni-filtered Cu Kα radiation, the diffraction angle (2θ) ranged from 5° to 40° with a step size of 0.02° and a time per step of 5°/min. The relative crystallinity of the samples was analyzed using Jade 6.0 software (Materials Data, California, USA) as detailed by Zhang et al. (2018).

2.8. Water- holding capacity

The water-holding capacity was assessed following a previously reported method with slight modifications by Yang, Ma, Bian, Mei, and Xie (2023). A sample of known weight (M_1) was mixed with distilled water at a material–liquid ratio of 1:20 (w/v) and stirred at room temperature for 30 min. Subsequently, the mixture was centrifuged at 2500 r/min for 10 min, the supernatant was discarded, and the precipitate was weighed. The water-holding capacity was calculated using the following formula:

$$\mathrm{WAI}\left(\frac{\mathrm{g}}{\mathrm{g}}\right) = \frac{M_2 - M_1}{M_1} \tag{1}$$

2.9. Iodine blue value

The sample (0.50 g) was setted volume to 100 mL with the preheated distilled water at 65.5 °C. The resulting mixture was stirred for 5 min at the same temperature in a thermostatic water bath. Subsequently, the solution was filtered, and 5 mL of the filtrate was transferred into a 50 mL volumetric flask. To this, 1 mL of 0.02 mol/L iodine standard solution was added. The solution was then diluted with distilled water to the mark, and the absorbance value of the sample was measured at 650 nm, denoted as A, with the reagent blank serving as the control, following the method outlined by Damat et al. (2023).The iodine blue value was calculated as follows:

$$\text{Iodine blue value} = \mathrm{A} \times 54.2 + 5. \tag{2}$$

2.10. Anthocyanin

Anthocyanin content was determined following established procedures (Giusti & Wrolstad, 2001). The sample (1 g) was combined with a 60% (v/v) ethanol–hydrochloric acid solution (pH 4.0) at a material–liquid ratio of 1:15 and subjected to ultrasonic extraction at 45 kHz and 40 °C for 60 min. The resulting solution was centrifuged at 8000 rpm for 10 min to isolate the supernatant, which was then combined and adjusted to a volume of 250 mL with distilled water. Anthocyanin content was quantified using a dual wavelength spectrophotometer (TU-1900, Puxi, Beijing, China) with distilled water as a blank.

2.11. Particle size analysis

Particle size distributions were analyzed using a laser diffraction particle size analyzer, specifically the Mastersizer 3000 (Malvern, UK), following the methodology outlined by Wang et al. (2020). The characterization of particle size distribution included parameters such as the volumetric weighted mean particle size D[4,3], median diameter (D50), and span, which is calculated as (D90–D10)/D50. Here, the D10, D50, and D90 values correspond to the 10th, 50th, and 90th percentiles of the total volume, assuming a spherical shape of particles.

2.12. Color analysis

Color analysis was performed using a colorimeter (UltraScan, HunterLab, USA) to assess color changes in the samples post-addition of PSPF. Parameters measured included lightness value (L*), red–green value (a*), and blue–yellow value (b*) as described by Tong et al. (2015). The samples were measured in triplicate for accuracy.

2.13. Scanning electron microscopy

Scanning electron microscopy (SEM) was utilized to observe the morphology of the samples using an SU-8600 SEM (Hitachi, Japan). Samples were mounted on an aluminum stub and sputter coated with gold before micrographs were taken at an accelerating voltage of 2.0 kV.

2.14. Statistical analysis

The data were presented as mean ± standard deviation (SD). Statistical analysis was performed using the Duncan test and one-way analysis of variance (ANOVA) in SPSS27 (SPSS Institute, USA) for multiple comparisons. Each experiment was repeated at least thrice, and differences were deemed significant at $P < 0.05$. Graphs representing the experimental results were generated using Origin 8.5 (Origin Lab, USA).

3. Results and discussion

3.1. Nutritional components of composite flours

The analysis of Fig. 1 and Supplementary material 1 revealed the nutritional composition of the composite flours, with the proximate composition of rice flour being in line with previous studies (Jiao et al., 2020). The protein content of PSPF was slightly higher than reported in literature (Rodrigues, Barbosa Junior, & Barbosa, 2016), while the moisture, fat, ash, and starch content were lower compared to previous data (Rodrigues et al., 2016). The total dietary fiber content was higher than reported (Jiang et al., 2022), and the anthocyanin content of PSPF was also higher than reported (Chiang et al., 2023), indicating variations in composition due to different varieties and processing methods (Senevirathna, Ramli, Azman, Juhari, & Karim, 2021a).

The findings from the study revealed that PSPF exhibited lower levels of moisture, fat, protein, starch, and amylose compared to rice flour, while showing higher levels of total dietary fiber and ash. Specifically, the amylose and moisture content in rice flour were approximately double that of PSPF. Furthermore, the total dietary fiber and ash contents in PSPF were approximately 5 times and 4 times higher than those in rice flour, respectively. With an increase in the proportion of PSPF in the mixture, there was a significant decrease in moisture, fat, protein, starch, and amylose, along with a significant increase in total dietary fiber and ash contents. The high ash content in PSPF may be attributed to its rich mineral and trace element content, such as calcium, iron, phosphorus, and selenium, which enhance the mineral composition of rice flour. Dietary fiber, being a group of indigestible carbohydrates, plays a crucial role in improving gastrointestinal function and regulating blood glucose and cholesterol levels. The abundant dietary fiber in PSPF can enhance the digestion and absorption rate of purple sweet potato and rice products. Additionally, the lower moisture content in purple sweet potato powder may positively impact food storage, while the protein content in purple sweet potato can optimize the amino acid profile of the mixed powder, providing a more balanced nutritional composition. The lower fat content in PSPF is advantageous for the development of low-fat food products. Amylose content is crucial for starch aging and regrowth, significantly influencing the taste of the final product. Changes in the content and proportion of starch, amylose, and amylopectin in the mixed powder can affect the gelatinization and thermodynamic properties of composite flours, as well as the texture and taste of the end product (Chang, Zhang, Xia, Kang, & Yan, 2022).

The results revealed that the anthocyanin content of PSPF was measured at 40.20 mg/100 g, a value lower than what has been reported in previous literature (Senevirathna, Ramli, Azman, Juhari, & Karim, 2021b). It is important to note that the quality of the purple sweet potato itself, as well as the processing method employed for PSPF, can both have an impact on the anthocyanin content. As illustrated in Fig. 1B, the addition of purple potato flour resulted in a significant increase in the anthocyanin content of the composite flours. This enhancement in anthocyanin content has the potential to not only improve the nutritional profile of the products but also enhance their color and flavor characteristics.

3.2. Thermal properties

The thermodynamic properties of various proportions of composite

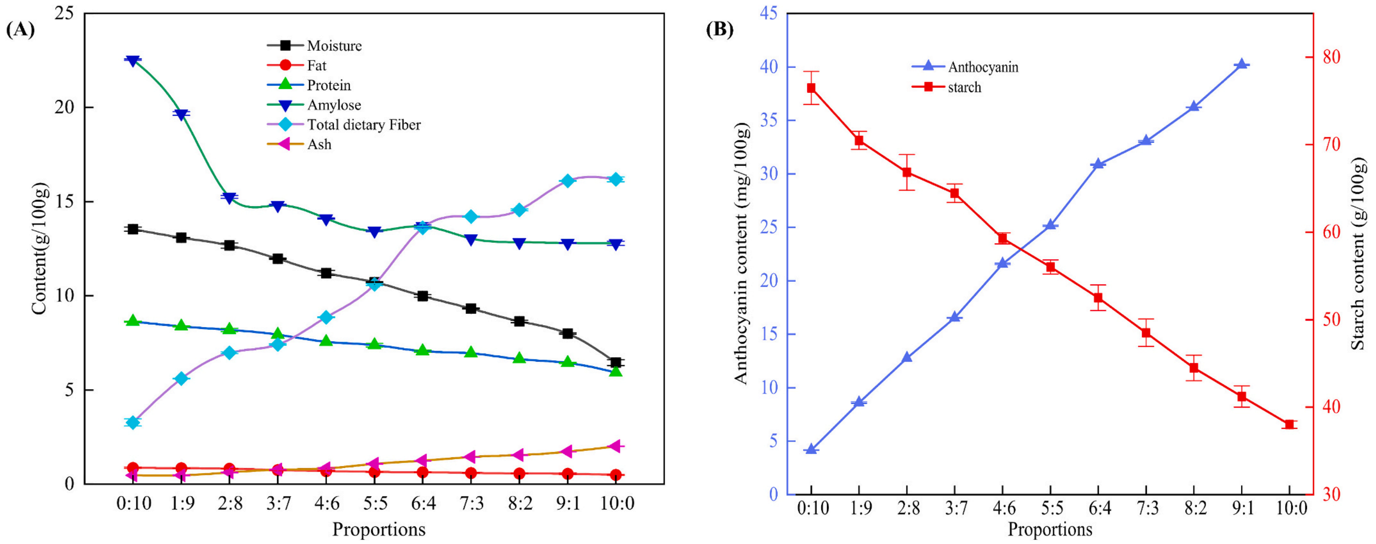

Fig. 1. Nutritional composition of composite flours from PSPF and rice flour in different proportions.

flours have been detailed in Table 1. Prior to mixing, the values of onset temperature (To), peak temperature (Tp), conclusion temperature (Tc), and enthalpy change (ΔH) for PSPF were recorded at 73.30 °C, 82.4 °C, 87.83 °C, and 0.06 J/g, respectively, while rice flour exhibited values of 67.59 °C, 80.83 °C, 88.30 °C, and ΔH of 5.11 J/g. Notably, the thermodynamic properties of PSPF observed in this study differ from those reported in existing literature (Shan et al., 2013), potentially due to variations in the PSPF variety. The lower ΔH value of PSPF suggests that it possesses reduced crystallinity and higher gelatinization, a characteristic that may be linked to the pre-cooking process involved in the production of PSPF.

Upon mixing, all composite flours exhibited a bimodal thermal curve. The initial peak of the DSC curve corresponded to the thermodynamic peak of PSPF, with the values of To, Tp, Tc, and ΔH decreasing with the addition of PSPF. The subsequent peak represented the thermodynamic peak of rice flour, where the To, Tp, and Tc values increased upon the addition of PSPF, while the ΔH values notably decreased, particularly at a compounded flour ratio of 4:6. This phenomenon may be attributed to the partial destruction of the starch structure of rice flour during the initial peak pasting stage, leading to a reduced requirement of temperature and energy for gelatinization (Zhang et al., 2023). Previous research by Mun and Shin (2018) indicated a positive correlation between amylose content, gelatinization temperature, and the formation of helical inclusions with hydrophobic properties, which hinder water ingress into starch granules. The lower amylose content in PSPF may facilitate easier gelatinization and processing of the composite flours. The thermal characteristics of composite flours mirror the internal starch's thermal properties. ΔH is associated with the number of double helices, the strength of interactions between starch molecules in the crystalline region, and increased relative crystallinity, making pasting more challenging. The incorporation of PSPF led to a reduction in the ΔH value of rice flour, signifying a decrease in the crystallinity of the composite flours, consistent with our own findings (Lange et al., 2021). The lower ΔH value is advantageous for product processing.

3.3. Pasting property

The analysis depicted in Fig. 2A and Supplementary material 2 revealed that the pasting temperature of composite flours exhibited an upward trend with increasing amounts of PSPF. This phenomenon was attributed to the distinctive microcrystalline structures of the two starch types (Kowsik & Mazumder, 2018). The intricate microcrystalline arrangement of PSPF necessitates more energy for water molecules to permeate. The elevated pasting temperature of PSPF could be linked to its higher content of well-ordered crystal structures or starch double helices, impeding water ingress and expansion of starch particles, thereby indicating the heat resistance of PSPF. As the proportion of PSPF rose, the viscosity of the mixture gradually declined, aligning with existing literature (Waterschoot, Gomand, Willebrords, Fierens, & Delcour, 2014). A notable reduction in peak viscosity was observed with

Table 1
Thermal properties of composite flours.

A:B	First Pasting Peak				Second Pasting Peak			
	To(°C)	Tp(°C)	Tc(°C)	△H(J/g)	To(°C)	Tp(°C)	Tc(°C)	△H(J/g)
0:10					67.59 ± 0.01^{a}	80.83 ± 0.16^{e}	88.30 ± 0.06^{e}	5.11 ± 0.01^{e}
1:9	67.84 ± 0.84^{a}	71.06 ± 0.07^{a}	75.91 ± 0.70^{a}	0.40 ± 0.01^{d}	74.42 ± 0.24^{a}	81.83 ± 0.27^{a}	88.97 ± 0.13^{a}	1.51 ± 0.02^{f}
2:8	69.23 ± 0.01^{b}	71.42 ± 0.56^{a}	77.06 ± 0.43^{b}	0.44 ± 0.03^{d}	76.75 ± 0.32^{b}	81.57 ± 0.55^{a}	89.13 ± 0.24^{a}	1.49 ± 0.04^{f}
3:7	69.96 ± 0.29^{bc}	72.45 ± 0.12^{ab}	78.77 ± 0.40^{c}	0.25 ± 0.02^{bc}	78.09 ± 0.04^{c}	82.30 ± 0.05^{a}	89.69 ± 0.19^{b}	1.47 ± 0.03^{f}
4:6	70.25 ± 0.13^{c}	73.85 ± 0.34^{c}	80.22 ± 0.15^{d}	0.21 ± 0.01^{c}	79.64 ± 0.27^{d}	83.41 ± 0.24^{b}	89.97 ± 0.02^{bc}	0.74 ± 0.02^{e}
5:5	70.57 ± 0.02^{c}	73.18 ± 0.01^{bc}	80.12 ± 0.09^{d}	0.14 ± 0.02^{abc}	80.06 ± 0.10^{de}	83.97 ± 0.41^{b}	90.36 ± 0.09^{cd}	0.62 ± 0.05^{d}
6:4	70.88 ± 0.06^{cd}	75.33 ± 0.49^{d}	80.09 ± 0.07^{d}	0.12 ± 0.01^{ab}	80.36 ± 0.16^{ef}	84.06 ± 0.10^{b}	90.31 ± 0.14^{cd}	0.52 ± 0.00^{c}
7:3	71.50 ± 0.04^{de}	75.61 ± 0.02^{d}	80.60 ± 0.03^{d}	0.10 ± 0.00^{a}	80.79 ± 0.08^{f}	83.35 ± 0.41^{b}	90.29 ± 0.09^{cd}	0.44 ± 0.03^{b}
8:2	71.92 ± 0.04^{ef}	75.60 ± 0.09^{d}	80.74 ± 0.05^{d}	0.09 ± 0.01^{a}	80.72 ± 0.02^{f}	83.76 ± 0.13^{b}	90.52 ± 0.07^{d}	0.31 ± 0.00^{a}
9:1	72.49 ± 0.05^{fg}	75.86 ± 0.06^{d}	80.94 ± 0.03^{d}	0.07 ± 0.00^{a}	80.90 ± 0.02^{f}	83.78 ± 0.15^{b}	90.65 ± 0.05^{d}	0.25 ± 0.01^{a}
10:0	73.30 ± 0.14^{g}	82.41 ± 0.36^{f}	87.83 ± 0.16^{e}	0.06 ± 0.00^{a}				

A:B is the mass ratio of PSPF to rice flour. Values are means of three replicates ± standard deviation. Values in the same column followed by same superscript letters are not significant different ($P < 0.05$).To:gelatinization onset temperature; Tp:gelatinization peak temperature; Tc: gelatinization conclusion temperature; ΔH: gelatinization enthalpy.

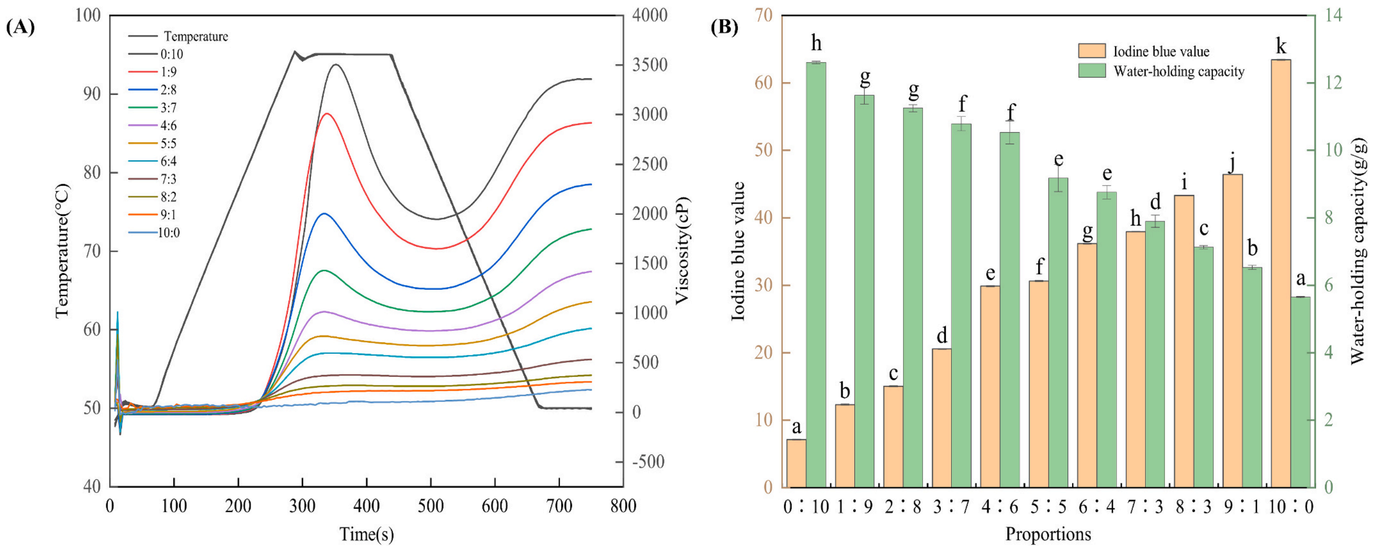

Fig. 2. RVA pasting curve of composite flours from PSPF and rice flour in different proportions (A), Water-holding capacity and Iodine blue values of composite flours from PSPF and rice flour in different proportions (B). Bars with different superscript letters are significantly different ($p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

increased PSPF content, underscoring its significant impact on blend viscosity, indicative of the weak water absorption capacity of starch granules in PSPF. The incorporation of PSPF led to a decrease in breakdown viscosity of the composite flour, suggesting an enhancement in gelatinization stability. Lower setback viscosity values imply a weaker aging trend, indicating that PSPF could bolster the anti-aging properties of the composite flours. Pasting curves of flours with varying PSPF proportions highlighted its substantial influence on the pasting properties of rice flour.

3.4. Water-holding capacity

The water-holding capacity of a food product plays a critical role in determining its properties, including elasticity, softness, and moisture retention, which in turn affect its overall utility and suitability for various applications. Analysis from B illustrates a gradual decline in water-holding capacity with an increasing proportion of PSPF in the composite flours. Specifically, the water-holding capacity of PSPF was measured at 5.65 g/g, approximately half of that observed in rice flour. This essential characteristic is influenced by various factors such as dietary fiber content, surface characteristics, specific surface area, and microstructure, as documented in previous studies (Yalegama, Karunaratne, Sivakanesan, & Jayasekara, 2013). The relatively low water-holding capacity of PSPF may be attributed to its compact particle structure, which hinders the easy ingress and retention of water molecules.

3.5. Iodine blue value

The iodine blue value serves as a metric for assessing the presence of free starches, indicative of whole flour cell breakage and structural integrity. This parameter is utilized to quantify the level of free starch content within a sample (Kaur, Panesar, Bera, & Kumari, 2014). A higher iodine blue value signifies a greater extent of cell destruction and the release of free starch within the cells, ultimately impacting the sensory attributes of the final product. As illustrated in Fig. 2B, a notable increase in the iodine blue value was observed with the addition of PSPF. This escalation can be attributed to the heightened cellular fragmentation of PSPF compared to the finer fragmentation observed in rice flour. With an increase in the proportion of PSPF in the blend, the degree of cellular fragmentation within the mixture also escalates. Processes such as pre-cooking, cutting, drying, and crushing can induce cell fragmentation, leading to an elevated iodine blue value, which could explain the comparatively high iodine blue value associated with PSPF.

3.6. Particle size

The particle size and distribution of starch granules play a crucial role in determining the structural and processing characteristics of starch gels, thus influencing the overall quality of food products (Chen, Schols, & Voragen, 2003). Analysis from Fig. 3 (**A** & **B**) revealed a normal distribution of particle sizes in the flours under study. Notably, the average particle size of PSPF was measured at 151 μm, surpassing the size of rice flour particles (109 μm). Discrepancies between the reported particle size of PSPF in this study and that in existing literature (Azeem, Mu, & Zhang, 2021) may be attributed to variations in processing methodologies. With an increase in the proportion of PSPF in the composite flours, the values of D10, D50, D90, and D[4,3] **(**Fig. 3C & Supplementary material 3**)** exhibited a substantial rise, indicating a corresponding increase in the particle size of the composite flour with the addition of PSPF. The uniformity of particle size distribution was assessed using the Span parameter, where a lower value denotes a more homogeneous distribution of particle sizes (Silva, Couturier, Berrin, Buléon, & Rouau, 2012). The peak of the particle size distribution curve shifted towards higher values, becoming more pronounced and narrower with the inclusion of PSPF. PSPF demonstrated a reduced Span value, suggesting a more uniform particle size distribution compared to rice flour. The incorporation of PSPF had a significant impact on the particle size distribution of the composite flours, leading to an increase in the average particle size and enhancing the uniformity of particle size distribution within the blends.

3.7. Color

Color is a critical attribute in fulfilling the sensory expectations of a food product, as it directly influences consumer appetite and overall enjoyment of the culinary experience (Auvray & Spence, 2008). The L* value represents brightness, while the a* value signifies the presence of red and green hues, with a positive a* value indicating a reddish tone and a negative value indicating a greenish hue. On the other hand, the b* value reflects the yellow and blue coloration of the product, with a positive b* value indicating a yellowish tint and a negative value

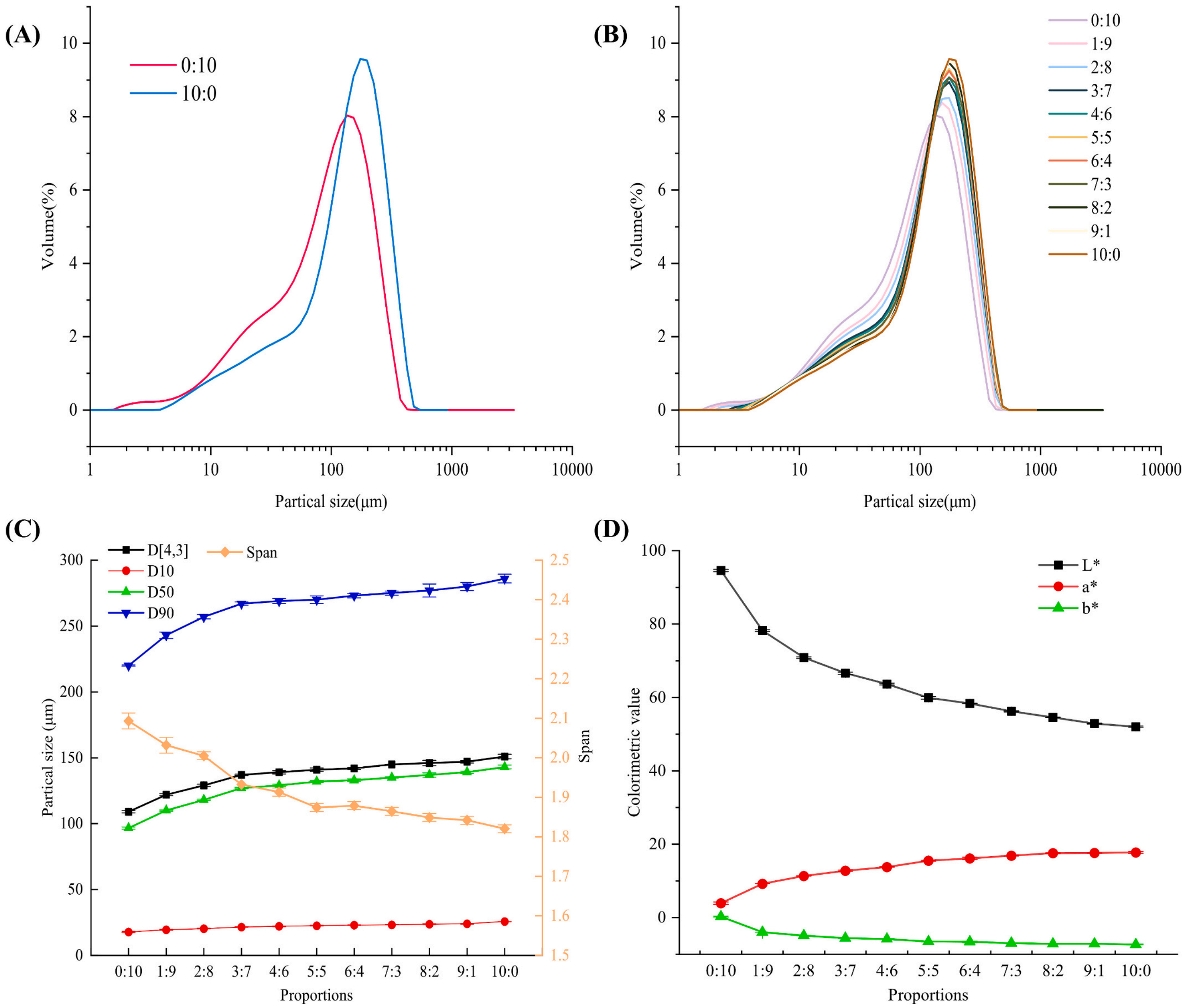

Fig. 3. Particle size distributions (A, B, C) and colors (D) of composite flours from PSPF and rice flour in different proportions.

suggesting a bluish shade. Analysis from Fig. 3D revealed that PSPF exhibited dark, reddish, and bluish tones, with the L*, a* and b* values surpassing those reported by Ahmed et al. (2010) but falling below values from another study (Hu et al., 2023). Discrepancies in color values may stem from variations in PSPF type and processing conditions. Incorporating PSPF at different levels altered the color profile of the flours, introducing red and blue hues to the blended powder. Increasing concentrations of PSPF in the blends notably reduced lightness (L*) compared to rice flour, while simultaneously decreasing b* values and elevating a* values. These outcomes suggest that the inclusion of PSPF led to darker, redder, and bluer coloration in the blends, possibly attributable to the high anthocyanin content present in PSPF. This observation aligns with findings in the literature (Meenakumari, Ravichandran, & Vimalarani, 2023).

3.8. Morphology

Fig. 4 illustrates the contrasting microscopic features of PSPF and rice flour. Rice flour particles displayed an uneven and irregular surface, with starch particles exhibiting a nearly spherical shape. In contrast, PSPF particles exhibited a smoother and irregular surface texture. This disparity in microscopic appearances can be attributed to the processing methods employed for each flour type. Rice flour was predominantly processed through crushing, while PSPF underwent pre-cooking, drying, and crushing stages. The distinctively smooth and irregular surface structure of PSPF particles indicates a complete breakdown of the original PSPF structure during processing, resulting in fragmented and agglomerated particles forming an irregular block structure with flat surfaces, sharp edges, and smooth cross-sections. This structural difference is a direct consequence of the processing procedures utilized for each flour. The compact and smooth appearance of the PSPF surface likely contributes to its lower water-holding capacity, given the altered physical characteristics resulting from the processing methods applied.

3.9. Fourier transform infrared spectroscopy

Fig. 5A illustrates a prominent and broad absorption peak spanning between 3700 and 3300 cm^{-1}, corresponding to the telescopic vibration peak of -OH, indicating the presence of numerous phenolic and alcohol hydroxyl groups in the composite flour. Additionally, a weaker vibrational absorption peak and stretching vibrational peak of the C—H bond were observed between 3000 and 2700 cm^{-1}, suggesting a minor

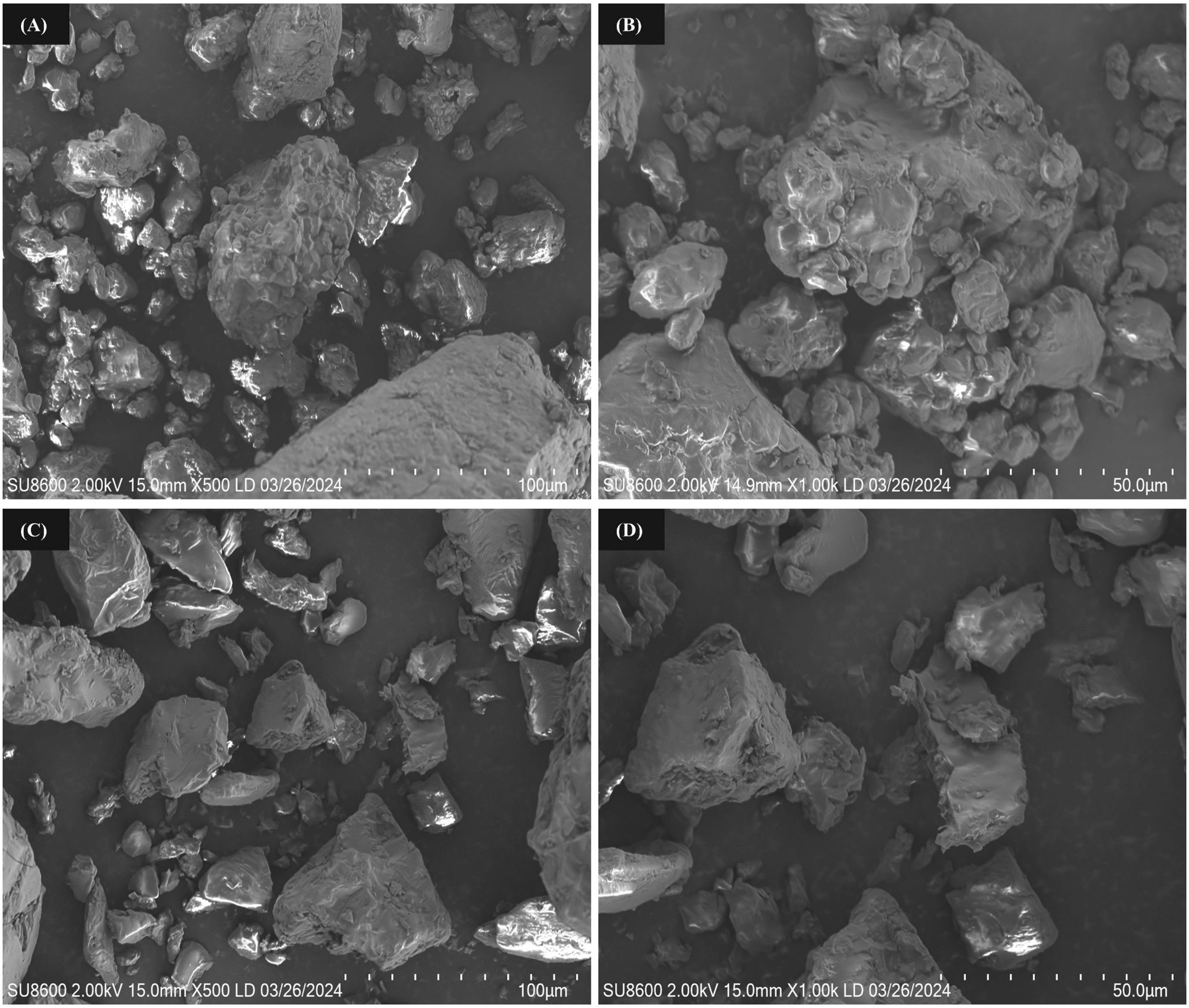

Fig. 4. SEM images of the rice (A, B) and PSPF(C, D) at 500X and 1000X.

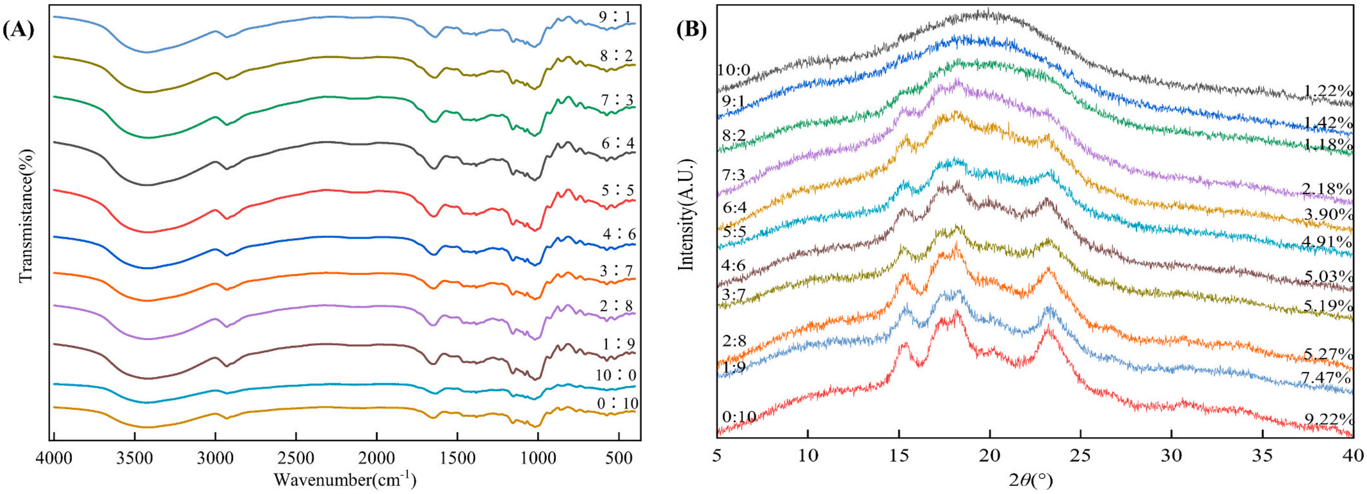

Fig. 5. FTIR (A) and XRD (B) of composite flours from PSPF and rice flour in different proportions.

presence of hydrogen on the saturated carbon atoms within the composite flours. A distinct absorption peak of C═O between 1620 and 1650 cm^{-1} suggests the existence of flavonoids within the composite flour. Furthermore, a subtle absorption peak in the stretching vibration peak of C═C in the aryl ring between 1520 and 1550 cm^{-1}, characteristic of flavonoids, was observed. The sample exhibited a robust absorption peak between 1140 and 1170 cm^{-1}, representing the alkyl stretching vibration peak. Absorption peaks attributed to benzene ring C—H were detected between 1023 and 865 cm^{-1}, indicating the presence of flavonoid polyphenolic structures in the composite flours (Zhou, Zhang, Jiang, Nie, & Bai, 2021). These results are in alignment with previous findings (Syarifin, Purnomo, & Fudholi, 2021). Notably, Fig. 5A demonstrates that the peak shapes of the composite flours remain consistent even with an increase in the proportion of PSPF. This suggests that the inclusion of PSPF does not alter the functional groups present in the composite flours.

3.10. *Crystalline structures*

Rice flour exhibits characteristic crystalline structures of A-type starch, as evidenced by distinct peaks at 15° and 23°, along with partially separated double peaks at 17° and 18°. This observation aligns with findings reported in the literature (Wu, McClements, Chen, Hu, & Liu, 2016). In contrast, PSPF lacks a specific crystalline structure, as depicted in Fig. 5B, which is consistent with conclusions drawn from thermal properties analysis. Notably, as the percentage of PSPF decreased, the intensity of certain diffraction peaks increased. The relative crystallinity of the blends decreased from 9.22% to 1.42% as the A-type crystalline diffraction peak gradually diminished, indicating that the addition of PSPF led to a reduction in the crystallinity of the mixtures. Furthermore, with a higher proportion of PSPF in the blends, the natural diffraction peaks exhibited a gradual weakening trend. According to Wang, Li, Copeland, Niu, and Wang (2015), increased crystal content and a more complete crystalline region result in higher and narrower diffraction peaks in the sample. These results suggest that the incorporation of PSPF effectively decreased the crystallinity of the blends, which could potentially have a beneficial impact on starch retrogradation.

4. Conclusion

PSPF is a nutritious raw-food material that can be added to rice flour. This study investigated the effects of combining different amounts of PSPF and rice flour to form composite flour combinations. The nutritional compositions and physicochemical properties of the composite flour were investigated.

The data obtained in the present work supplies a scientific basis for the formulation and processing of purple potato-rice products with high nutritional value. The properties of the composites with different proportions are quite different. PSPF is highly nutritious, with higher levels of anthocyanin, total dietary fiber, and ash than rice flour. The addition of PSPF increases the nutritional value and functional properties of composite flours. After blending, all composite flours show bimodal thermal curve. As the proportion of PSPF increased, thermal parameters (To, Tp, and Tc) increased whereas the enthalpy (ΔH) decreased. PSPF has lower crystallinity and higher gelatinization. The iodine blue value increased as the addition of PSPF, while the water-holding capacity decreased. The addition of PSPF significantly affects the particle size distributions of composite flours, and makes the particle size distribution more uniform. PSPF makes the color of blends darker, redder, and bluer. The surface of rice flour particles was uneven and irregular, whereas the surface of PSPF particles was smoother and irregular. The composite flour contain many phenolic, flavonoids and alcohol hydroxyl groups, PSPF does not change the functional groups of composite flour. The addition of PSPF effectively decreased the crystallinity of the blends. PSPF decreased the viscosity of the mixture and improved the gelatinization stability and anti-aging ability of composite flours. The addition of PSPF effectively decreased the crystallinity of the blends. Addition of PSPF is conducive to the processing of the product.

In conclusion, the addition of PSPF changes the nutrition, color and physicochemical properties of composite flour. This study provides valuable insights into selecting the optimal PSPF ratio to meet specific processing requirements for various purple potato-rice products, facilitating the comprehensive utilization of purple potato resources. Nevertheless, it is important to acknowledge that the assessment of physical and chemical parameters of raw material powders encompasses a wide range of factors, and the scope of this study is inherently limited in its coverage of these extensive indexes. Further research into processing technology, texture, and sensory evaluations is warranted to enhance the understanding and application of raw material ratios in product development.

CRediT authorship contribution statement

Yanting Liu: Writing – original draft, Visualization, Validation, Methodology, Data curation. **Wangyang Shen:** Funding acquisition, Conceptualization. **Weiping Jin:** Visualization, Validation, Methodology. **Fang Li:** Software, Methodology, Formal analysis. **Xuan Chen:** Visualization, Validation, Methodology. **Xiwu Jia:** Visualization, Validation. **Hongyan Cai:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available within the manuscript, and material is available with authors.

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Appendix A. Supplementary data

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