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# Characterization of flours from some underutilized carbohydrate sources of Thailand for potential food applications

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## ABSTRACT

Northern Thailand's underutilized crop flours were examined for morphology, chemical composition, thermal, and techno-functional properties to broaden carbohydrate sources and assess their potential as plant-based food analogs and other food ingredients. Samples were as follows: Elephant foot yam (A), and Purple yam or Greater yam (DA-P), Water yam (DA-W), Five-leaf yam (DP), *D. daurica* Prain & Burkill (DD), and Lesser yam (DE). Scanning electron micrographs revealed varied starch granule shapes and size ranging from 9 to 31 μm. XRD showed A-type crystallinity for sample A, B-type for DA-P, DA-W, DP, and DE, and C-type for DD. DP flour has the highest protein and starch content. DD and DE flours had the highest fat and fiber content with the least amylose content. DP, DA-P, and A flours displayed excellent thickening capacity, whereas DD and DE flours exhibited low viscosity and resistance to disintegration induced by heat and shear. DA-W flour exhibits moderate physico-chemical properties, rendering it versatile for a multitude of applications. Gelatinization enthalpy ( $\Delta H$ ) ranged from 3.46 J/g to 8.14 J/g, indicating DA-P granular structure had more crystallites while A flour had lower thermostability. All flours exhibited unique characteristics, offering diverse options as texturizing agents for food analog formulation.

## 1. Introduction

Plant-based meat analogs (PMAs) have attracted significant interest due to their environmental sustainability, health benefits, animal welfare protection, high production efficiency, and cost-effectiveness (McClements & Grossmann, 2021). Meat analogs have been acknowledged as a promising approach to replacing animal meat in the human diet by imitating the appearance, flavor, and fibrous texture of animal meat (Pietsch, Emin, & Schuchmann, 2017). The rising demand for plant-based meals is driven by several factors, including lifestyle changes, growing consumer awareness of sustainable food production, and a growing interest in alternative diets (Rawal, Annamalai, Bhandari, & Prakash, 2023). Plant-based diets offer health benefits in preventing a

range of non-communicable diseases (NCDs) due to their higher fiber and lower fat content, and they also encourage a greater diversity of plant foods (Cutroneo et al., 2022; Gibbs & Leung, 2023; Kim et al., 2019).

PMAs typically consist of various ingredients, including 50–80% water content, 20%–50% proteins (comprising 4–20% non-textured based proteins and 10–25% vegetable textured based proteins), 2%–30% carbohydrates (such as gums, fibers, starch, etc.), 0%–15% lipids, 3–10% flavoring agents, 0–5% coloring agents, and binding agents 1–15% (Boukid, 2021; Egbert & Borders, 2006; Kyriakopoulou, Keppler, & van der Goot, 2021). Proteins are mainly responsible for creating the gel network and providing the backbone of meat-like fibrous structures. Carbohydrates aid in "sub-layer transformation" by cross-linking

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proteins through phase separation and also function as fillers, thickeners, and binders. Lipids are essential for determining the juiciness, tenderness, smoothness, flavor, nutritional value, and storage stability of PMAs. The molecular interactions occurring among these macromolecules as well have a substantial impact on the final textural characteristics and quality of the products (Chen, Chen, Zhang, Wang, & Wang, 2023).

Carbohydrates play critical roles in plant-based product development and can constitute 1% up to 50% or more in plant-based meat products, ranging from simple carbohydrates (e.g., sucrose and glucose) to polysaccharides (e.g., starch, fiber, gum, modified cellulose, etc.). They demonstrate essential and fundamental properties such as hydration, gelation, dehydration, degradation and reducing power. They are widely used to improve the texture by creating fibrillation of textured proteins, mimicking animal skin and connective tissue, acting as a fat or fat tissue substitute, and producing color, flavor, and aroma (Huang et al., 2022). Flours and starches in plant-based product formulations are typically derived from staple crops including wheat, soybeans, corn, potato, and cassava. Wheat gluten and soybean protein are two of the most popular ingredients as protein and carbohydrate sources in PMAs, offering a meat-similar texture with significant protein content, contributing to the nutritional and structural characteristics of PMAs (Zhang et al., 2021). Exploring alternative ingredients for consumers facing wheat gluten intolerance and soy allergy is widespread. There's a rising interest in utilizing carbohydrates from locally sourced flours, reflecting a growing trend toward exploring underutilized crops for sustainable and diverse food sources.

Apart from the staple crops, people in the northern part of Thailand are relying on local crops as an alternative carbohydrate source, such as yams (*Dioscorea* spp.) and konjac, or elephant's foot yam (*Amorphophallus* spp.), which are naturally grown in the forest area. These starchy crops are utilized in many rural areas, especially among indigenous and tribal peoples (Maneenoon, Sirirugsa, & Sridith, 2008; Thapayai, 2004; Thapayai, Jitrit, & Yasook, 2017). They are potentially climate-resilient, sustainable, biodiverse, nutrient-dense, and locally available (Li, Yadav, & Siddique, 2020). These underutilized crops offer unique advantages in terms of sustainability, food diversity, and low allergenicity, making

them promising candidates for incorporation into various food products, including PMAs. Consequently, diversifying food sources with composite plant-based proteins offers a sustainable and effective strategy for developing plant-based meat alternatives. This paper aims to explore the potential of flours derived from underutilized crops as sustainable, diverse, and allergen-friendly alternatives to be used in PMAs production by highlighting their nutritional content, functional properties, and unique characteristics and benefits of these underutilized crops.

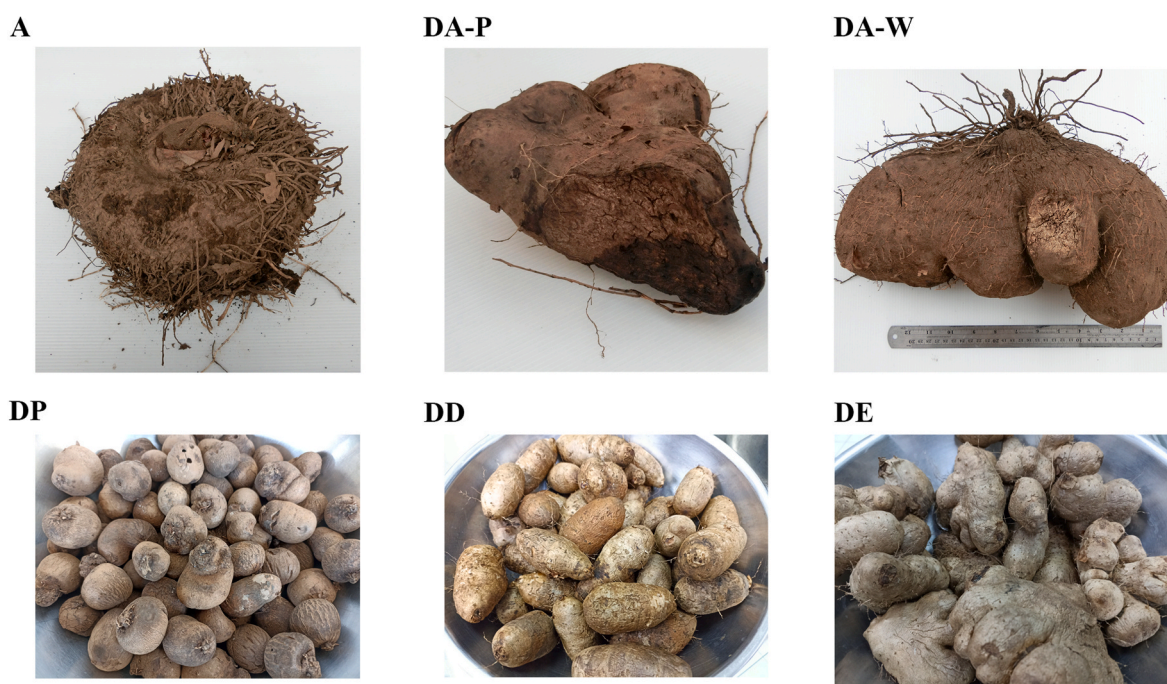
## 2. Materials and methods

### 2.1. Sample collection and flour preparation

Underutilized crops were surveyed and selected from local markets in the northern part of Thailand. Six crops (Fig. 1) were selected according to the screening criteria, including the availability, consumption, and possibility of cultivation. According to Thai traditional practices and knowledge involving the use of these crops, including toxicological information that can be recalled, all of these six crops are safe for human consumption. The details of each crop are shown in Table 1. Fresh samples were prepared into flour according to the methods described by Aprianita, Vasiljevic, Bannikova, and Kasapis (2014) with some modifications. Samples were processed through cleaning, peeling, washing, slicing into 1–3 cm thickness, and soaking in 0.5%g/mL of sodium metabisulfite solution for 10 min to prevent

**Table 1**  
Abbreviation, scientific name and common name of the samples.

Abbreviation	Scientific name	Common name
A	<i>Amorphophallus</i> spp	Konjac
DA-P	<i>Dioscorea alata</i> (purple)	Purple yam, Ube, or Greater yam
DA-W	<i>Dioscorea alata</i> (white)	Water yam, Winged yam
DP	<i>Dioscorea pentaphylla</i>	Five Leaf Yam
DD	<i>Dioscorea daunaea</i> Prain & Burkill	–
DE	<i>Dioscorea esculenta</i>	Lesser yam, Potato yam, Chinese yam, Wild yam



**Fig. 1.** Photographs of the samples A: *A. paeoniifolius*, DA-P: *D. alata*-purple DA-P: *D. alata*-white, DP: *D. pentaphylla*, DD: *D. daunaea* Prain & Burkill, and DE: *D. esculenta*. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

discoloration. The sliced samples were dried at 50 °C in a tray dryer (Kluay NamThai, Bangkok, Thailand) until the final moisture content reached approximately less than 13%. The dried chips went through the milling process using a hammer mill (Chiangrai packaging, Thailand) and then sieved through a 150 µm. Flour samples were packed in aluminum foil bags and stored at -20 °C for no more than 24 months before being analyzed.

## 2.2. Determination of chemical composition

The proximate composition of flour samples including moisture, protein, fat, ash, and fiber content was analyzed according to AOAC (2000). Amylose and total starch content were determined using an amylose/amylopectin test kit (Megazyme, K-AMYL) and a total starch assay kit (Megazyme, K-TSTA).

## 2.3. Determination of granules morphology

### 2.3.1. Granule morphology

The flour samples were mounted on aluminum stubs with conductive carbon adhesive tape, vacuum-dried, and coated with gold. The granule morphology of flours was studied by field emission scanning electron microscope or FESEM (MIRA, Tescan) at 10 kV accelerating voltage, with a magnification of 3000X and a distance of 9.9–10.0 mm.

### 2.3.2. Crystalline structure

The crystalline structure of flour was analyzed by X-ray diffractometer or XRD (X'Pert Pro MPD, PANalytical). The operation conditions were: target voltage 40 kV, target tube current 30 mA, with Cu Kα radiation. The samples were scanned in a range of 2θ = 5–40° at a scanning rate of 0.4°/min. at room temperature. The percentage crystallinity was calculated using a X'Pert HighScore Plus.

## 2.4. Physicochemical properties and functional properties

### 2.4.1. Water absorption capacity (WAC) and oil absorption capacity (OAC)

The flour sample (1 g) was mixed with 10 ml of distilled water and kept at room temperature for 24 h. The supernatant was decanted (Cornejo & Rosell, 2015). OAC was done with the same procedure with 10 ml of soybean oil instead. WAC and OAC were calculated using the following formula.

$$\text{WAC or OAC (g/g)} = \frac{\text{Sample weight after centrifugation} - \text{dry sample weight}}{\text{dry sample weight}} \quad (1)$$

### 2.4.2. Emulsion activity (EA) and emulsion stability (ES)

Emulsion activity (EA) and stability (ES) were determined according to the method described by Naiker, Gerrano, and Mellem (2019). The flour sample (1 g) was mixed with 5 ml of distilled water and 5 ml of soybean oil. The mixture was mixed and then centrifuged at 1100 rpm for 5 min. The height of the emulsifying layer was recorded, then the mixture was heated at 80 °C for 30 min and re-centrifuged again. The height of the emulsifying layer after heating was recorded. The EA and ES were calculated using the following formula.

$$\text{EA (\%)} = \frac{\text{Height of emulsified layer (cm)}}{\text{Total height of the mixture (cm)}} \times 100 \quad (2)$$

$$\text{ES (\%)} = \frac{\text{Height of emulsified layer after heating (cm)}}{\text{Height of the mixture before heating (cm)}} \times 100 \quad (3)$$

### 2.4.3. Foaming capacity (FC) and foaming stability (FS)

Foaming capacity (FC) and stability (FS) were determined according to the method described by Naiker et al. (2019). The flour sample (1 g)

was mixed with 50 ml of distilled water. The mixture was homogenized for 2 min. The height of the foam was recorded after homogenization and after standing for 1 h. The FC and FS were calculated using the following formula.

$$\text{FC (\%)} = \frac{\text{Vol. after shear (ml)} - \text{vol. before shear (ml)}}{\text{Vol. before shear (ml)}} \times 100 \quad (4)$$

$$\text{FS (\%)} = \frac{\text{Vol. of foam at 1 h (ml)}}{\text{Initial vol. of foam (ml)}} \times 100 \quad (5)$$

### 2.4.4. Swelling power (SP) and solubility (SOL)

The swelling power (SP) and solubility (SOL) of the flour sample were determined according to the method described by Leach (1959). The flour sample (0.1 g) was mixed with 10 ml of centrifuge tube and heated in a water bath at 60, 70, 80, or 90 °C for 30 min with agitation. The suspension was centrifuged at 1,000×g for 15 min. The supernatant was decanted into an evaporating dish and dried at 105 °C for 24 h. After drying, the residue was weighed and used for solubility calculation. The sediment of swollen granules was weighed, and swelling power was calculated using the following formula.

$$\text{Solubility (\%)} = \frac{\text{Weight of residue after drying (g)} \times 400}{\text{Weight of dry flour sample (g)}} \quad (6)$$

$$\text{Swelling power (\%)} = \frac{\text{Weight of sediment paste (g)}}{\text{Weight of dry flour sample (g)} \times (100 - \% \text{solubility})} \times 100 \quad (7)$$

## 2.5. Pasting properties

Pasting properties of flour samples were analyzed using a rapid visco-analyzer (RVA). Flour sample (3 g) were mixed with 25 ml of distilled water. The samples were analyzed using following settings (Srichuwong, Sunarti, Mishima, Isono, & Hisamatsu, 2005): heating from 50 to 95 °C at 6 °C/min (after an equilibration time of 1 min at 50 °C), a holding period at 95 °C for 5 min, cooling from 95 to 50 °C at 6 °C/min and a holding phase at 50 °C for 2 min. The constant rotating speed of the paddle was 160 rpm.

## 2.6. Thermal properties

The thermal properties of flour samples were analyzed using differential scanning calorimetry or DSC (DSC3+, Mettler Toledo) according to the methods described by Han, Xing, Han, Guo, and Zhu (2021). Flour sample (3.0 mg) was weighed into a 40 µl aluminum crucible and distilled water was added in a 1:2 (g/mL) ratio of flour/water. The pan was sealed and stood for 1 h, and the sample was heated from 20 to 100 °C at a heating rate of 10 °C/min. Sealed empty cans were used as references. The onset temperature (T<sub>o</sub>), peak temperature (T<sub>p</sub>), conclusion temperature (T<sub>c</sub>), and gelatinization enthalpy (ΔH) were obtained, and all measurement was performed in triplicate.

## 2.7. Statistical analysis

All data was analyzed using analysis of variance (ANOVA) at a 95% significance level. Duncan's multiple range test was conducted to separate sample means. The software used was IBM SPSS Statistics 26. Data was presented as means ± standard deviation (SD), and all tests were conducted in triplicate. The correlation matrix between chemical compositions and physicochemical parameters of flours was assessed using a Pearson correlation analysis.

### 3. Results and discussion

#### 3.1. Chemical composition

The proximate compositions of all flours are shown in Table 2. Significant differences in all compositions were found among families and species. The ash content in flour samples was in the range of 0.11 (DA-W) to 0.30% (DP). DD and DE contained similar ash contents (0.20% and 0.22%, respectively). The results were in accordance with Shanthakumari, Mohan, and de Britto (2008), in which DP had the highest ash content and almost all minerals, e.g., Na, K, Ca, P, Fe, and Cu, compared to DA and DE in the same study. The ash content of all flour samples was lower than conventional flours: rice flour (0.39% dry basis (db)), cassava flour (1.06% db), and soybean flour (4.23% db) (Tharise, Julianti, & Nurminah, 2014).

The highest protein content was DP (9.25%), followed by DE (8.42%), DA-P (6.15%), A (5.41%), DD (5.30%), and DA-W (5.23%). The protein content of DA, DE, and DP was consistent with those previously reported in fresh samples, in the range of 0.6–18.7%, 5.6–10.5%, and 6.48–9.18%, respectively (Obidiegwu, Lyons, & Chilaka, 2020). DD and A flours contained higher protein content than that previously reported, which is 2.32% (Maneenoon et al., 2008) and in the range of 1.4–3.4% (Laignier et al., 2021), respectively. There were significant differences in protein content among flours ( $p < 0.05$ ). Protein content influences many functional properties of flour, e.g., solubility, flavor binding, emulsification, viscosity, gelation, texture, and dough formation, and is thereby important in the determination of the final characteristics of food products (Bohrer, 2019; Meade, Reid, & Gerrard, 2005). The protein content of all flour samples was lower than in wheat flour but higher than other roots and tubers like cassava flour (1.50–4.98%), sweet potato (3.40%) (Moongngarm, 2013; Tharise et al., 2014), and comparable to rice and maize flour (Adeyeye & Akingbala, 2015; Ahmed & Islam, 2018; Moawad, Rizk, Kishk, & Youssif, 2018). Because gliadin and glutenin are not found in these tubers, their flours could be used as an alternate source to wheat flour in plant-based analogs for celiac disease patients (Nehra, Marietta, & Murray, 2013).

DA-P and DP contained the lowest fat content (0.17 and 0.18%, respectively). Fiber and fat content are remarkably high in DD and DE (4.64 and 6.62% (db), and 1.42 and 1.47% (db), respectively). The fiber content in DA and DE was consistent with previous studies, while DP contained less fiber content than previously reported 5.14–7.24% (Obidiegwu et al., 2020). The fiber content in all flours is higher than rice flour (0.74%), cassava flour (2.62%), and soybean flour (2.35%) (Tharise et al., 2014). The fiber content of DD and DE was comparable to that of unripe banana flour reported by Moongngarm (2013), ranging from 5.11 to 8.82%. High fiber content is the benefit of plant-based foods over animal-based foods. With the high fiber content of these flours, they can be used as partial fat replacers or incorporated into products to decrease caloric content, increase complex carbohydrate content, and improve binding properties, cooking yield, and textural characteristics in plant-based meat products (Hygreeva, Pandey, & Radhakrishna, 2014). In comparison to wheat flour, these flours contained lower protein, fat, and ash content but higher fiber content (Tharise et al., 2014). Application of flours from these underutilized

crops to create composite flour containing high protein and fiber content as wheat flour substitutes for certain foods is practicable. Flour with a high starch and protein content is required as a great binder. They offer advantages in forming complex gels; these networks effectively entrap water and other compounds. This results in stronger bonds between components, helping to achieve higher retention in the meat matrix during processing (Pintado & Delgado-Pando, 2020).

There are significant differences in total starch content among all samples ( $p < 0.05$ ). The starch content was 66.22% for A and ranged from 63.16% (DE) to 79.52% (DP) for yam flours. The total starch content in yams varies according to region, ranging from 42.86 to 64.29% (India), 62.42–68.29% (China), 74.66–78.32% (Sri Lanka), and 78.83% (Australia) (Aprianita, Purwandari, Watson, & Vasiljevic, 2009; Li, Zhang, & Bhandari, 2019; Senanayake, Ranaweera, Bamunuarachchi, & Gunaratne, 2012; Shanthakumari et al., 2008). The amylose content of DD and DE was very low compared to all samples (14.01% and 12.32%, respectively). The amylose content of all yam flours was consistent with studies previously reported, ranging from approximately 9 to 30% (Riley, Bahado-Singh, Wheatley, Ahmad, & Asemota, 2008; Riley, Bahado-Singh, Wheatley, & Asemota, 2014; Seoud, Nawaz, & Arêas, 2013; Zakari, Mohammed, Medugu, & Sandra, 2014). According to previously reported by Syah and Hasbullah (2020), A flour contained lower starch and amylose content. However, the study by Suriya, Baranwal, Bashir, Reddy, and Haripriya (2016) showed that flour preparation had a significant impact on the amylose content of A flour. There are also many factors affecting the chemical composition of the crops, including the maturity stage of the crops, harvesting, and climatic and environmental factors (Maneenoon et al., 2008).

#### 3.2. Granule morphology

##### 3.2.1. Granule morphology and size

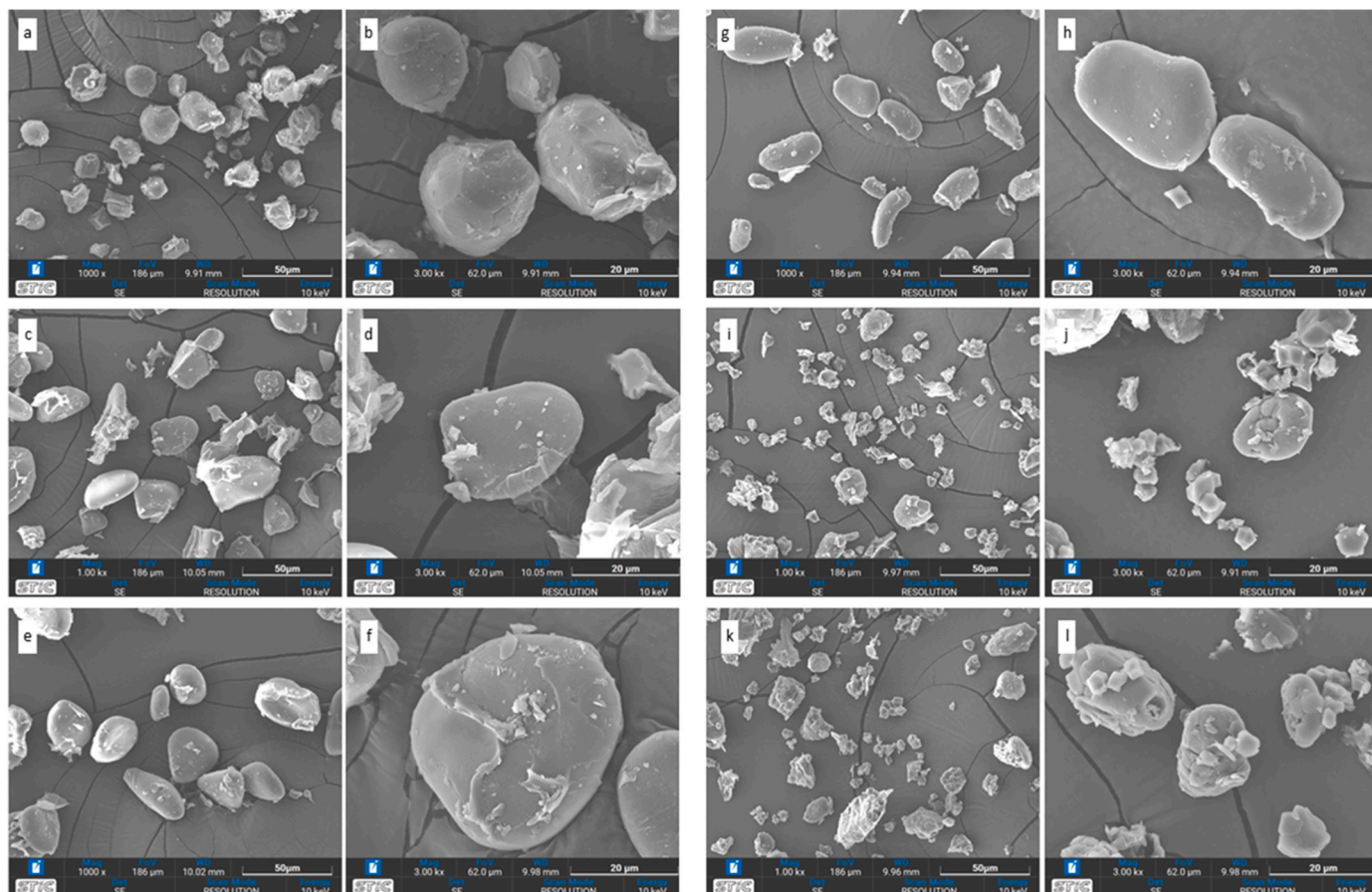
Scanning electron microscopy (SEM) in Fig. 2 illustrates the variation in morphology of each flour at various magnifications. The granular size of starch is also an important determinant for suitability in certain food applications (Freitas, Paula, Feitosa, Rocha, & Sierakowski, 2004; León, Barrera, Pérez, Ribotta, & Rosell, 2006). The size of the flour granules ranged from 9 to 31  $\mu\text{m}$  and the shape ranged from round to irregular (Table 3). They vary in size, shape, and surface roughness under the same milling conditions. According to starch granule size categorized by Lindeboom, Chang, and Tyler (2004), DA-P, DA-W, and DP flours are large granules (>25  $\mu\text{m}$ ) with an oval-oblong and elliptical shape. Granules are round with medium size (10–25  $\mu\text{m}$ ), whereas DD and DE granules are found to be similar with a much smaller size (5–10  $\mu\text{m}$ ) and contain a mixture of irregular oval and round granules. From the micrographs, all flour granules were observed to have proteins, lipids, or fiber fragments adhering to the surface. A flour granule is consistent with the previous study by Moorthy, Unnikrishnan, and Lakshmi (1994) that reported a round or polygonal granule with a size of 3–30  $\mu\text{m}$ . The granular size of DA was depending on the cultivated area, ranging from 30 to 45  $\mu\text{m}$  for those cultivated in Sri Lanka (Jayakody, Hoover, Liu, & Donner, 2007) and 28–47.2  $\mu\text{m}$  in Africa (Otegbayo et al., 2007). DA-P, DA-W, and DP granules showed a smoother surface than DD and DE. The DE granules in this study were correlated with those

**Table 2**  
Chemical composition of flour samples.

Samples	Water (%)	Ash (%)	Protein (%)	Fat (%)	Fiber (%)	Starch (%)	Amylose (%)
A	5.56 ± 0.31 <sup>c</sup>	0.25 ± 0.00 <sup>b</sup>	5.41 ± 0.18 <sup>d</sup>	0.27 ± 0.02 <sup>c</sup>	2.56 ± 0.28 <sup>c</sup>	66.22 ± 0.70 <sup>c</sup>	19.28 ± 0.34 <sup>d</sup>
DA-P	6.46 ± 0.40 <sup>b</sup>	0.18 ± 0.00 <sup>d</sup>	6.15 ± 0.12 <sup>c</sup>	0.17 ± 0.06 <sup>c</sup>	1.60 ± 0.34 <sup>d</sup>	67.24 ± 0.94 <sup>d</sup>	27.07 ± 1.73 <sup>a</sup>
DA-W	5.86 ± 0.14 <sup>c</sup>	0.11 ± 0.00 <sup>e</sup>	5.23 ± 0.05 <sup>e</sup>	0.45 ± 0.02 <sup>b</sup>	1.55 ± 0.42 <sup>d</sup>	74.55 ± 1.18 <sup>b</sup>	24.34 ± 0.32 <sup>c</sup>
DP	5.95 ± 0.14 <sup>c</sup>	0.30 ± 0.03 <sup>a</sup>	9.25 ± 0.04 <sup>a</sup>	0.18 ± 0.05 <sup>c</sup>	1.30 ± 0.32 <sup>d</sup>	79.52 ± 1.20 <sup>a</sup>	25.36 ± 0.78 <sup>b</sup>
DD	6.47 ± 0.19 <sup>b</sup>	0.20 ± 0.01 <sup>cd</sup>	5.30 ± 0.01 <sup>de</sup>	1.42 ± 0.15 <sup>a</sup>	4.64 ± 0.37 <sup>b</sup>	72.91 ± 1.10 <sup>c</sup>	14.01 ± 0.74 <sup>e</sup>
DE	7.83 ± 0.18 <sup>a</sup>	0.22 ± 0.00 <sup>c</sup>	8.42 ± 0.13 <sup>b</sup>	1.47 ± 0.07 <sup>a</sup>	6.62 ± 0.35 <sup>a</sup>	63.16 ± 0.98 <sup>f</sup>	12.32 ± 0.31 <sup>f</sup>

\*Values expressed mean ± standard deviation. Data of different alphabets in the same column were different with statistical significance ( $p < 0.05$ ).

\*\*A, DA-P, DA-W, DP, DD, and DE indicates *A. paeoniifolius*, *D. alata* (purple), *D. alata* (white), *D. pentaphylla*, *D. daunaea* Prain & Burkill, and *D. esculenta*, respectively.



**Fig. 2.** Scanning electron micrographs of flour samples: (a) A1000x, (b) A3000x, (c) DA-P1000x, (d) DA-W3000x, (e) DA W1000x, (f) DA-W3000x, (g) DP1000x, (h) DP3000x, (i) DD1000x, (j) DD3000x, (k) DE1000x, (l) DE3000x, respectively.

Note: A, DA-P, DA-W, DP, DD, and DE indicate *A. paeoniifolius*, *D. alata* (purple), *D. alata* (white), *D. pentaphylla*, *D. daunaea* Prain & Burkill, and *D. esculenta*, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Table 3**

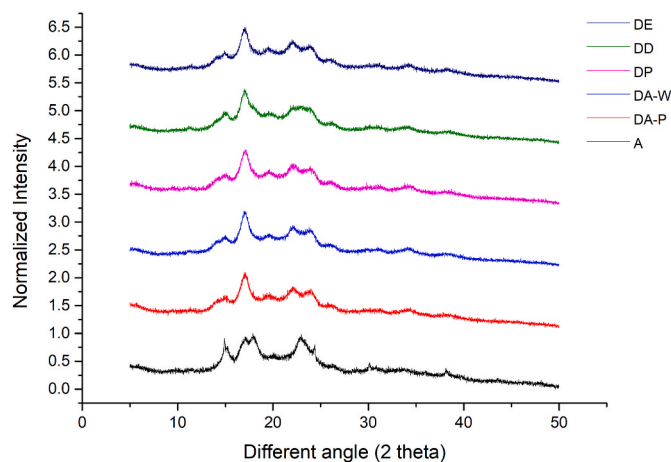
Morphological characteristics of flour granules (shape and size) estimated from scanning electron micrographs acquired on the flour samples. X-ray diffraction patterns and crystallinity (%).

Samples	Granular shape	Granular size (µm)	Crystallinity (%)	Crystalline pattern
A	Round	13.75 ± 5.64 <sup>c</sup>	36.64	A-type
DA-P	Oval-oblong, elliptical	22.64 ± 7.44 <sup>b</sup>	34.57	B-type
DA-W	Oval-oblong, elliptical	30.19 ± 6.10 <sup>a</sup>	34.11	B-type
DP	Oval-oblong, elliptical	23.99 ± 8.48 <sup>b</sup>	34.50	B-type
DD	Round, irregular shape	9.90 ± 4.97 <sup>d</sup>	37.52	C-type
DE	Irregular shape	9.34 ± 4.33 <sup>d</sup>	38.67	B-type

\*Values expressed mean ± standard deviation. Data of different alphabets in the same column were different with statistical significance ( $p < 0.05$ ).

\*\*A, DA-P, DA-W, DP, DD, and DE indicates *A. paeoniifolius*, *D. alata* (purple), *D. alata* (white), *D. pentaphylla*, *D. daunaea* Prain & Burkill, and *D. esculenta*, respectively.

previously reported in the range of 1.11–11.21 µm (Jayakody et al., 2007; Riley et al., 2008). Most yam starch granules range from 2 to 50 µm in size with shapes varying from spherical, oval, to polygonal depending on the species, as reported by Cornejo-Ramírez et al. (2018) and Jiang et al. (2012). Small granular sizes of DD and DE flour are desired for food products requiring a smooth texture.



**Fig. 3.** X-ray diffraction pattern of flour samples: (a) A, (b) DA-P, (c) DA-W, (d) DP, (e) DD, (f) DE

Note: A, DA-P, DA-W, DP, DD, and DE indicate *A. paeoniifolius*, *D. alata* (purple), *D. alata* (white), *D. pentaphylla*, *D. daunaea* Prain & Burkill, and *D. esculenta*, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### 3.2.2. Crystalline structure

The X-ray diffraction patterns of flour granules are shown in Fig. 3. A flour exhibited an A-type crystalline structure with strong diffraction peaks at  $2\theta$  values of 15°, 17°, 18°, and 23°. This agrees with the

crystalline structure of *A. paeoniifolius* starch reported by Sukhija, Singh, and Riar (2016). However, some studies also reported that *A. paeoniifolius* exhibited a C-type crystalline structure (Kandekar, Abhang, Pujari, & Khandelwal, 2021; Reddy et al., 2014). The DA-P, DA-W, DP, and DE samples showed B-type crystalline structure with a strong sharp peak at  $2\theta$  values of  $17^\circ$ , strong peaks at  $15^\circ$ ,  $22^\circ$ , and  $24^\circ$ , and a small peak at  $19^\circ$ . DD showed a broad, wide peak at  $23^\circ$  instead of sharp separate peaks at  $22^\circ$  and  $24^\circ$ , representing a C-type crystalline structure. Yam starches presented a C-type X-ray diffraction pattern in most previous studies (Lu, Liu, Yu, & Wang, 2022). There is no study reported on the crystallinity of DD. The relative crystallinity (RC) of samples ranged from 34.11% to 38.67% for the DA-W and DE, respectively (Table 3). Amylose content has an impact on the percent crystallinity and, as a result, influences the crystalline pattern (Parker & Ring, 2001). This study demonstrates a negative correlation between RC and amylose content, indicating that amylopectin with short-branched chains typically contributes to the crystalline structure of starch granules, while amylose has the potential to disrupt the crystalline packing of amylopectin (Cheetham & Tao, 1998). Tuber starches exhibited a B-type crystalline structure because of their high amylose content. Low amylose or high amylopectin content results in a high number of branch chains and leads to more points for degradation. C and A-type crystalline structures were therefore found to be more digestible than B-type crystalline structures (Riley et al., 2014).

### 3.3. Physicochemical and functional properties

#### 3.3.1. pH and bulk density

There are significant differences in pH and bulk density among samples ( $p < 0.05$ ) as shown in Table 4. The pH of flour samples was almost neutral and in a range of 6.08 (DA-P) to 6.49 (DD). The pH of flour is important for flour-based product processing since it can identify the desired quality of final products. Previous studies reported that pH influences flour solubility and emulsifying activity (Adepeju, Gbadamosi, Adeniran, & Omobuwajo, 2011). The internal pH and the iso-electric point (pI) of meat analogs strongly affect the water holding capacity as well. The bulk density of flour samples ranged from  $0.64 \text{ g/cm}^3$  (DA-W) to  $0.77 \text{ g/cm}^3$  (DP). Bulk density is crucial in food powder handling, determining packaging, storing, and processing (Ezeocha, Omodamiro, Oti, & Chukwu, 2011). DP flour was the coarsest flour and was suitable to be used as a food thickener. DA-W flour was the smoothest flour and might be used as an ingredient for instant and complementary foods among samples (Akpata & Akubor, 1999).

**Table 4**  
Physicochemical properties of flour samples.

Functional properties	A	DAP	DAW	DP	DD	DE	
pH	$6.37 \pm 0.08^b$	$6.08 \pm 0.07^d$	$6.22 \pm 0.04^c$	$6.12 \pm 0.03^d$	$6.49 \pm 0.03^a$	$6.35 \pm 0.03^b$	
Bulk density ( $\text{g/cm}^3$ )	$0.69 \pm 0.00^d$	$0.67 \pm 0.00^e$	$0.64 \pm 0.00^f$	$0.77 \pm 0.00^a$	$0.76 \pm 0.00^b$	$0.70 \pm 0.01^c$	
WAC (g/g)	$1.83 \pm 0.05^c$	$2.96 \pm 0.04^a$	$2.56 \pm 0.02^b$	$1.90 \pm 0.06^c$	$1.40 \pm 0.05^d$	$1.20 \pm 0.03^e$	
OAC (g/g)	$1.18 \pm 0.00^b$	$1.19 \pm 0.01^b$	$1.17 \pm 0.01^b$	$1.03 \pm 0.03^c$	$1.18 \pm 0.03^b$	$1.27 \pm 0.01^a$	
EA (%)	$3.00 \pm 1.00^e$	$38.00 \pm 2.00^a$	$24.00 \pm 4.00^c$	$28.00 \pm 2.00^b$	$11.33 \pm 1.15^d$	$40.00 \pm 0.00^a$	
ES (%)	$8.67 \pm 2.31^e$	$25.33 \pm 1.15^d$	$34.00 \pm 2.31^c$	$70.00 \pm 4.00^a$	$10.67 \pm 1.15^e$	$43.33 \pm 3.06^b$	
FC (%)	$16.67 \pm 3.06^e$	$26.00 \pm 2.00^c$	$26.67 \pm 3.06^c$	$46.67 \pm 3.06^a$	$33.33 \pm 3.06^b$	$36.00 \pm 3.46^b$	
FS (%)	$98.23 \pm 1.76^a$	$98.06 \pm 2.68^a$	$96.49 \pm 1.17^a$	$98.04 \pm 0.81^a$	$96.46 \pm 2.04^a$	$95.81 \pm 0.36^a$	
% Solubility	60 °C	$17.26 \pm 0.30^c$	$12.80 \pm 0.34^e$	$15.91 \pm 0.53^d$	$14.94 \pm 0.56^d$	$22.37 \pm 0.81^b$	$32.80 \pm 1.06^a$
	70 °C	$18.79 \pm 0.42^c$	$14.88 \pm 0.36^e$	$17.97 \pm 0.49^d$	$14.99 \pm 0.33^e$	$25.25 \pm 0.31^b$	$46.00 \pm 0.39^a$
	80 °C	$24.34 \pm 0.51^c$	$16.13 \pm 0.07^d$	$24.09 \pm 0.84^c$	$16.64 \pm 0.30^d$	$30.95 \pm 1.72^b$	$62.46 \pm 1.58^a$
	90 °C	$24.99 \pm 1.40^c$	$17.91 \pm 2.92^d$	$24.35 \pm 0.28^c$	$20.31 \pm 1.07^d$	$36.01 \pm 2.13^b$	$69.04 \pm 0.99^a$
% Swelling power	60 °C	$6.91 \pm 0.25^c$	$8.04 \pm 0.24^a$	$7.47 \pm 0.24^b$	$5.36 \pm 0.05^d$	$4.48 \pm 0.28^e$	$5.50 \pm 0.34^d$
	70 °C	$6.00 \pm 0.05^d$	$7.70 \pm 0.66^b$	$8.39 \pm 0.39^a$	$6.74 \pm 0.20^c$	$5.51 \pm 0.08^d$	$7.08 \pm 0.39^{bc}$
	80 °C	$10.44 \pm 0.37^d$	$12.13 \pm 0.26^c$	$15.23 \pm 0.36^a$	$12.67 \pm 0.31^{bc}$	$14.73 \pm 0.49^a$	$13.49 \pm 0.95^b$
	90 °C	$15.40 \pm 0.81^{bc}$	$14.44 \pm 0.62^c$	$16.50 \pm 0.58^{ab}$	$14.63 \pm 0.67^c$	$16.81 \pm 0.76^a$	$16.56 \pm 0.59^{ab}$

\*Values expressed mean  $\pm$  standard deviation. Data of different alphabets in the same row were different with statistical significance ( $p < 0.05$ ).

\*\*A, DA-P, DA-W, DP, DD, and DE indicates *A. paeoniifolius*, *D. alata* (purple), *D. alata* (white), *D. pentaphylla*, *D. daumaea* Prain & Burkill, and *D. esculenta*, respectively. WAC, OAC, EA, ES, FC, and FS stand for water absorption capacity, oil absorption capacity, emulsion activity, emulsion stability, foaming capacity, and foaming stability, respectively.

#### 3.3.2. Water absorption capacity (WAC) and oil absorption capacity (OAC)

WAC was significantly different among flour samples ( $p < 0.05$ ). The WAC is a critical quality characteristic in plant-based meat substitutes because it determines the juiciness and ability to retain water of protein and create a protein gel network (Taghian Dinani, de Jong, Vardhanabhuti, & van der Goot, 2024). The highest value of WAC was found in DA-P flour ( $2.96 \text{ g/g}$ ) and the lowest was found in DE flour ( $1.27 \text{ g/g}$ ). The WAC shows a positive correlation with the amylose content in flour samples and a negative correlation with the percent crystallinity of starch at a significance level of  $p < 0.05$  (Fig. 4). The increased amylose content enhances the penetration of water molecules by forming clusters through hydrophobic interactions and hydrogen bonds, resulting in a significant increase in the WAC of starch (Zhang et al., 2023).

The WAC of DA-P and DA-W were much higher than the WAC of wheat flour ( $1.40 \text{ g/cm}^3$ ), cassava flour ( $205 \text{ g/cm}^3$ ), and potato flour ( $210 \text{ g/cm}^3$ ) reported by Etong, Mustapha, Lawrence, Jacob, & Oladimeji (2022). The high WAC of DA-P and DA-W flours not only gives them the potential to be used as raw materials in the processing of simulated fat with juicy, lubricious textures and an adhesive effect (Zhao et al., 2022), but also makes them a great binder in plant-based analogs, enhancing overall water retention and cooking yields in reformulated meat products. It might also be used as a wheat flour alternative in batter composition, as high WAC improves the percentage pick-up of the batter and the film-forming properties of the coating materials that inhibit oil penetration and hence reduce the oil uptake and calorie content of fried products (Kurek & Šćetar, 2017).

The highest value of OAC was found in DE flour ( $1.27 \text{ g/g}$ ) and the lowest was found in DP flour ( $1.03 \text{ g/g}$ ). A, DA-P, DA-W, and DD showed no significant differences at  $p < 0.05$ . DE and DD flours had low WAC and high OAC because of their small granular sizes (Bala, Handa, Mridula, & Singh, 2020). The degree of dissolution of flour particles and surface areas rises as the granular size decreases, resulting in higher water penetration and the tendency of the solid matrix to interact with water (Wu et al., 2021). OAC is an important parameter as it contributes to the flavor, mouthfeel, and texture of food. The flour with high OAC has potential to be used for flavor retention. The highest OAC of DE means it might be useful as a raw material for meat formulations, meat replacers, extenders, sausages, and other foods where oil absorption is desired.

WAC and OAC are based on several factors such as the presence of lipid, protein, and fiber, particle size, amount of damaged starch, the ratio of amylose to amylopectin, intra- and intermolecular forces (Adebowale, Sanni, & Onitilo, 2008; Singh, Singh, Kaur, Sodhi, & Gill,

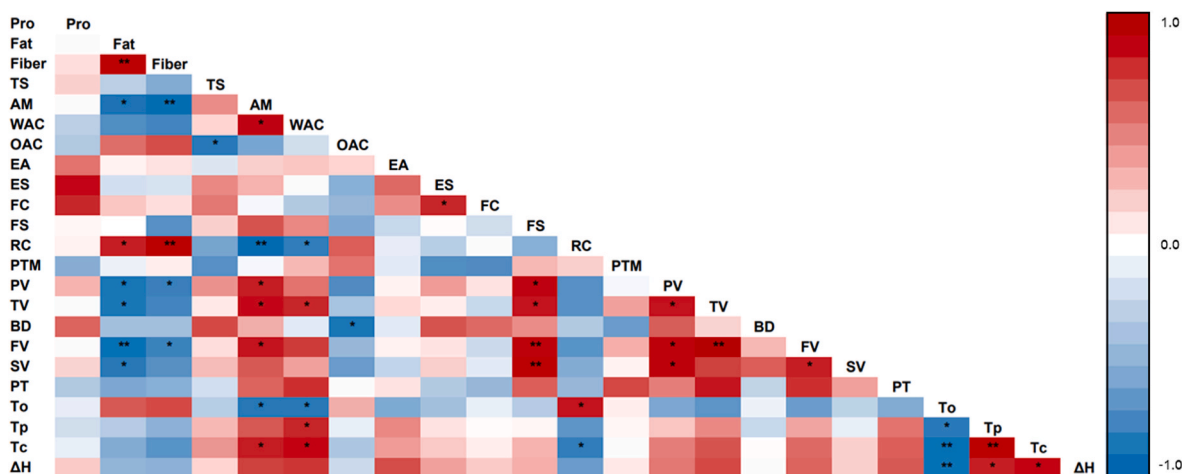


Fig. 4. Pearson's correlation matrix among flour chemical composition and physicochemical properties. \* and \*\* indicate significant at  $p < 0.05$  and  $p < 0.01$ . Note: Fat, fat content; Fiber, fiber content; TS, total starch content; AM, amylose content; WAC, water absorption capacity; OAC, oil absorption capacity; EA, emulsion activity; ES, emulsion stability; FC, foaming capacity; FS, foaming stability; RC, relative crystallinity; PTM, pasting temperature; PV, peak viscosity; TV, trough viscosity; BD, breakdown viscosity; FV, final viscosity; SV, setback viscosity; PT, peak time; To, onset temperature; Tp, peak temperature; Tc, conclusion temperature;  $\Delta H_{gel}$ , enthalpy of gelatinization.

2003). The OAC also depends on intrinsic factors like amino acid composition, protein conformation, and surface polarity or hydrophobicity (Suresh, 2013). The presence of both hydrophilic and hydrophobic parts favors 3D protein network formation with water or lipids (Bhuiyan, Yeasmen, & Ngadi, 2024).

### 3.3.3. Emulsion activity (EA) and emulsion stability (ES)

Yam flours showed significantly different emulsion activity (EA) ranging from 11.33 (DD) to 40.00% (DE), and emulsion stability (ES) ranging from 10.67 (DD) to 70.00% (DP). The lowest emulsifying activity and stability was observed in A flour (3.00% and 8.67%, respectively). Emulsifying properties in flour are associated with the surface-active properties of proteins, which form electrostatic repulsions around oil droplets. These abilities vary based on composition, content, hydrophobicity, solubility, and conformational stability of proteins and non-protein components such as carbohydrates (Kaushal, Kumar, & Sharma, 2012). A flour had considerable protein content; however, the differences could be attributed to the nature of different types of protein. DE flour is the best emulsifier, while DP showed the highest ES among all flours. DE flour exhibits high EA values, likely attributed to its high fiber content. Aluko, Mofolasayo, and Watts (2009) suggested that carbohydrates like starch and fiber may enhance EA and ES by forming bulky barriers between oil droplets, slowing their coalescence rate. Similarly, the high ES of DP flour may be due to certain polysaccharides that increase system viscosity, aiding in emulsion stabilization (Dickinson, 1994). DA-P and DE can be used in emulsion-type meat analogs to improve textural properties, reduce oil leakage, and purge loss as they contribute to high EA and ES (Kyriakopoulou et al., 2021).

### 3.3.4. Foaming capacity (FC) and foaming stability (FS)

The FC of all flours ranged between 16.67 (A) and 46.67% (DP). While foam stability (FS) ranged from 95.81 (DE) to 98.23% (A) with no significant difference ( $p < 0.05$ ). DP and DE have high FC because of the high protein content (8.69 and 7.82%, respectively), as FC refers to the amount of interfacial area that can be created by protein (Fennema, 1996). A flour exhibited the lowest ability to produce foam but showed the formed foam had the highest stability to resist collapse over time. The low FS of DE flour may be due to its high protein and fat content. Fat interferes with the protein network that creates foam structure, while high protein content advocates protein-protein interactions that lead to foam collapse (Toews & Wang, 2013). Flours with high FC could form large air bubbles surrounded by a thinner, less flexible protein film,

likely to collapse and resulting in lower foam stability (Jitngarmkusol, Hongsuwankul, & Tananuwoong, 2008). Foam has an effect on the appearance, consistency, and texture of many foods (Akubor, 2007). Emulsifying and foaming properties might be useful for the application as a plant-based egg and milk substitute in aerated food products, e.g. cakes, bread, ice cream, and whipped cream.

### 3.3.5. Swelling power (SP) and solubility (SOL)

Table 4 shows the SP and SOL of flour samples from 60 to 90 °C. %SP of different yam species ranged from 14.44% (DA-P) to 16.81% (DD), whereas %SOL ranged from 17.91% (DA-P) to 69.04% (DE) at 90 °C. The %SP and %SOL of samples increased as the heating temperature increased.

All flour samples exhibited a high increase in SP between 70 and 80 °C, where the crystal region in starch granules starts to melt and undergo gelatinization. DA-P flour had the lowest SOL due to its highest amylose content, which acts as both a diluent and an inhibitor of starch granule swelling (Tester & Morrison, 1990). At all temperatures, DE flour exhibited the highest SOL, indicating a greater extent of starch degradation and more amylose leaching from granules into water (Itagi & Singh, 2012). Because of the high amylopectin content, the SP value was significantly higher ( $p < 0.05$ ) in DA-W, DD, and DE. DA-P, DA-W, and A flour exhibited significant SP at 60 °C (8.04, 7.47, and 6.91%, respectively). The ability of these flour to swell rapidly at low temperature shows their potential for use as a cold swelling flour and thickener. The rapid swelling characteristics are also useful as foundation material for providing an instantaneous support matrix for protein particles and other ingredients (Dobson, Laredo, & Marangoni, 2022). The SP of all flours in this study were higher than that of native corn starch 2.3 and 10.9 g/g at 40 °C and 90 °C, respectively (Hong, Cheng, Lee, & Peh, 2015). The SOL and SP tend to increase as the granular size decreases, as observed in DD and DE (Ahmed, Taher, Mulla, Al-Hazza, & Luciano, 2016; Bala et al., 2020). Small starch granules have a higher surface area than large granules and lead to higher SOL, WAC, and SP (Lindeboom et al., 2004). Aside from the amylose/amylopectin ratio, other things that affect SOL and SP are the sources, the inter-associative forces between the amorphous and crystalline domains, and the presence of other components (e.g., lipids, protein, fiber, and phosphorus) (Kumoro, Retnowati, & Budiayati, 2012).

### 3.4. Pasting properties

The pasting properties of flour samples are presented in Table 5. The pasting characteristics are crucial for a suitable selection for use as a thickener, binder, and other food applications. The pasting temperature (PTM) of all flours was between 79.4 and 90.7 °C. DE flour required the least time for cooking (4.4 min). Short cooking times are preferred for foods processed at high temperatures for a short time, like retorts (canned foods) and sterilized foods. DA-P flour requires the highest temperature (90.7 °C) and the longest time to cook (6.5 min). This might be due to the larger granular size having a greater barrier to heat transfer and diffusion of water, leading to lower swelling of starch granules and increased PT (Marshall, 1992). DP flour exhibited the highest peak viscosity (PV) (4271 cP) and the lowest PTM (79.4 °C) among all flours, contributing to the highest starch content. A high PV of DA-P and DP flours indicates starches can swell extensively but are also susceptible to breakage during cooking (Singh et al., 2003) while also suggesting a suitability for use as plant-based thickeners. Their good gelation properties are ideal for use as binding agents in plant-based analogs, as the increased viscosity after heating is conducive to improving the texture and juiciness of simulated fat (Bohrer, 2019). Low PV of DD and DE flours enhances the printability of 3D muscle-like products (Kazir & Livney, 2021) and also makes them suitable for weaning and supplementary food applications. The lowest trough viscosity (TV) values of DE (143 cP) and DD (266 cP) indicated the highest stability of the hot paste after cooking. DP had the highest breakdown viscosity (BV) values (2249 cP), indicating weak cross-linking within starch granules and resulting in a low-stable paste. Whereas low BD values of DA-P and DE flour indicate a better ability of flour paste to resist heat and shear-induced disintegration, which is significant in application and will be suitable for products that need to be treated at high temperatures, e. g., baked products.

The final viscosity (FV) of DA-P, DP, and A was higher than the other three samples, indicating a higher ability to form viscous paste after cooking and cooling (Shafie, Cheng, Lee, & Yiu, 2016), but it also shows that the paste will be less stable after cooling with a higher gelation capacity than the other three flours. DD and DE flour had much lower FV (385 and 233 cP), showing the ability of DD and DE flour paste to resist the shear stress during stirring. Higher fat content in DD and DE flours generally leads to lower viscosity values and reduced gelatinization of starch granules during heating, resulting in weaker viscosity retention and less pronounced retrogradation during cooling (Devi, Sindhu, & Khatkar, 2020), as shown in the significant negative correlation of fat content with PV, TV, and SV at  $p < 0.05$  and FV at  $p < 0.01$ .

A and DP flours showed high setback viscosity (SV) values (807 and 808 cP), which are ideal for refrigerated products and products where

retrogradation is desirable, e.g., noodles, soups, or sauces, corresponding to a higher retrogradation tendency after gelatinization. DD and DE flours are more resistant to retrogradation due to their lower amylose content and are suitable for low-viscous foods, for example, salad dressing, ice cream, spreads, confectionaries, and beverages. Amylose content showed a significant positive correlation ( $p < 0.05$ ) with peak viscosity (PV), trough viscosity (TV), and final viscosity (FV). Many studies confirmed the negative correlation between amylose content and peak viscosity, as amylose restricts the swelling of starch granules after gelatinization (Juhász & Salgó, 2008; Karakelle, Kian-Pour, Toker, & Palabiyik, 2020). This demonstrates that the amount of amylose may not be the only factor that influences pasting properties, but also its characteristics. Li, Zhang, Wei, Zhang, and Zhang (2014) found that the PV, FV, BV, and SV of amylose were higher than those of amylopectin. However, it is not only the amylose/amylopectin ratio that influences the pasting characteristics of starch but also other factors, e.g., the branch chain lengths of amylopectin and interactions with other components in the flours. The low amylose content and particle size of DD and DE flours might be the most important factors affecting their unique pasting properties. Liu, Weber, Currie, and Yada (2003) also indicated that the smaller size of the granules contributes to the higher PTM and lower PV. Altogether, DP flour showed similar pasting profiles to potato starch but higher PV, while DA-P was similar to cassava starch (Horstmann, Belz, Heitmann, Zannini, & Arendt, 2016). A, DA-P, and DP flour had higher PV than potato flour reported by Zhang et al. (2023), and this indicates that these flours are superior in binding properties. DA-W has similar pasting properties to potato flour and has potential as a substitute binder for potatoes.

### 3.5. Thermal properties

The thermal properties of different flour samples measured by DSC are summarized in Table 5. The gelatinization enthalpy ( $\Delta H$ ) of different flours decreased in the order of DA-P > DP > DA-W > DE > DD > A. The gelatinization temperatures (onset temperature ( $T_o$ ), peak temperature ( $T_p$ ), and conclusion temperature ( $T_c$ ) of different yam flour varieties ranged between 60.06 and 64.17 °C, 80.12 and 82.10 °C, 88.23 and 92.51 °C, respectively. A flour showed lower values of all parameters at 63.98, 79.61, and 88.32 °C, respectively. All yam varieties and A flour exhibited gelatinization temperatures within the range that previous studies reported (Ashri et al., 2014; Meng, Liang, Shuai, Xiong, & Zhong, 2015). Starch structure and degree of crystallinity had a significant positive correlation with  $T_o$  ( $p < 0.05$ ), as the dissociation of the double helix and crystalline starch crystal regions demands more heat and higher temperatures. These attributes contribute to structural stability against heating (Barichello, Yada, & Coffin, 1991; Yamin, Lee, Pollak, &

**Table 5**  
Pasting properties of flour samples.

Samples		A	DA-P	DA-W	DP	DD	DE
Pasting properties	PTM (°C)	89.10 ± 0.52 <sup>b</sup>	90.65 ± 2.34 <sup>a</sup>	82.37 ± 2.13 <sup>c</sup>	79.37 ± 0.47 <sup>d</sup>	85.28 ± 0.92 <sup>b</sup>	84.70 ± 4.10 <sup>bc</sup>
	PV (cP)	2688.00 ± 10.82 <sup>c</sup>	3397.33 ± 107.58 <sup>b</sup>	1710.00 ± 39.95 <sup>d</sup>	4271.00 ± 30.51 <sup>a</sup>	704.00 ± 15.40 <sup>e</sup>	401.33 ± 19.86 <sup>f</sup>
	TV (cP)	1888.33 ± 28.92 <sup>c</sup>	3265.00 ± 54.67 <sup>a</sup>	1261.33 ± 12.01 <sup>d</sup>	2021.33 ± 73.58 <sup>b</sup>	266.00 ± 6.08 <sup>e</sup>	143.67 ± 7.37 <sup>f</sup>
	BD (cP)	799.67 ± 19.50 <sup>b</sup>	132.33 ± 72.432 <sup>e</sup>	448.67 ± 37.53 <sup>c</sup>	2249.67 ± 43.68 <sup>a</sup>	438.00 ± 11.27 <sup>c</sup>	257.67 ± 12.50 <sup>d</sup>
	FV (cP)	2695.67 ± 40.55 <sup>c</sup>	3811.33 ± 15.18 <sup>a</sup>	1588.00 ± 35.68 <sup>d</sup>	2829.67 ± 92.65 <sup>b</sup>	385.33 ± 12.10 <sup>e</sup>	233.33 ± 10.12 <sup>f</sup>
	SV (cP)	807.33 ± 12.34 <sup>a</sup>	546.33 ± 66.67 <sup>b</sup>	326.67 ± 25.58 <sup>c</sup>	808.33 ± 85.24 <sup>a</sup>	119.33 ± 6.11 <sup>d</sup>	89.67 ± 3.06 <sup>d</sup>
	PT	5.33 ± 0.07 <sup>b</sup>	6.53 ± 0.35 <sup>a</sup>	4.93 ± 0.07 <sup>c</sup>	4.82 ± 0.10 <sup>c</sup>	4.87 ± 0.07 <sup>c</sup>	4.42 ± 0.04 <sup>d</sup>
	Thermal properties	$T_o$ (°C)	63.98 ± 0.15 <sup>a</sup>	60.60 ± 0.08 <sup>e</sup>	61.39 ± 0.13 <sup>d</sup>	61.83 ± 0.05 <sup>c</sup>	64.17 ± 0.11 <sup>a</sup>
$T_p$ (°C)		79.61 ± 0.19 <sup>e</sup>	82.10 ± 0.10 <sup>a</sup>	81.76 ± 0.16 <sup>b</sup>	80.68 ± 0.18 <sup>c</sup>	80.63 ± 0.09 <sup>c</sup>	80.12 ± 0.09 <sup>d</sup>
$T_c$ (°C)		88.32 ± 0.26 <sup>e</sup>	92.51 ± 0.10 <sup>a</sup>	91.46 ± 0.21 <sup>b</sup>	90.70 ± 0.06 <sup>c</sup>	89.47 ± 0.11 <sup>d</sup>	88.23 ± 0.06 <sup>e</sup>
$T_c - T_o$ (°C)		24.35 ± 0.33 <sup>e</sup>	31.90 ± 0.11 <sup>a</sup>	30.07 ± 0.09 <sup>b</sup>	28.86 ± 0.01 <sup>c</sup>	25.30 ± 0.11 <sup>d</sup>	24.63 ± 0.37 <sup>e</sup>
$\Delta H_{gel}$ (J/g)		3.46 ± 0.20 <sup>f</sup>	8.14 ± 0.14 <sup>a</sup>	5.54 ± 0.23 <sup>c</sup>	6.11 ± 0.23 <sup>b</sup>	4.10 ± 0.09 <sup>e</sup>	4.65 ± 0.11 <sup>d</sup>

\*Values expressed mean ± standard deviation. Data of different alphabets in the same row were different with statistical significance ( $p < 0.05$ ).

\*\*A, DA-P, DA-W, DP, DD, and DE indicates *A. paeonifolius*, *D. alata* (purple), *D. alata* (white), *D. pentaphylla*, *D. daumaea* Prain & Burkill, and *D. esculenta*, respectively.

\*\*\*PV, peak viscosity; TV, trough viscosity; BD, breakdown viscosity; FV, final viscosity; SB, setback viscosity; PTM, pasting temperature; PT, peak time;  $T_o$ , onset temperature;  $T_p$ , peak temperature;  $T_c$ , conclusion temperature;  $\Delta H_{gel}$ , enthalpy of gelatinization.

White, 1999). The variance among varieties could be attributed to amylopectin chain length disparity, while within the same variety, distinctions may arise from genetic, environmental, maturity, and seasonal factors (Aprianita et al., 2014). DA-P exhibited the highest gelatinization temperature and  $\Delta H$ , indicating greater crystallite in granular structure and thermo-stability that require more energy to destabilize amylose and amylopectin molecules (Kaur, Singh, Ezekiel, & Guraya, 2007; Simsek, Martinez, Daglioglu, Guner, & Gecgel, 2014). In contrast, the granular structure of A flour is more amorphous and less resistant to gelatinization, and this might contribute to the low amylose content (19.28%). DD and DE showed similar gelatinization temperatures and  $\Delta H$ . Flours with a lower gelatinization temperature could be applied in food processing with a low temperature, such as batter coating or processed meat products. It is also beneficial in food processing as it requires a shorter cooking time and lower heat (Snow & O'Dea, 1981). Zhang, Li, Zhang, Drago, and Zhang (2016) investigated the impact of enthalpy changes in starch blends on extrudate quality. Their research revealed that higher enthalpy changes in the blends were correlated with reduced fibrous texture in the resulting extrudates. The  $\Delta H$  values for A, DD, and DE flour were low (3.46, 4.10, and 4.65 J/g, respectively), which meant that they could be used in ingredient blends that would help make fibrous protein extrudates.

#### 4. Conclusions

The results of this study showed that flour from 6 different underutilized crops found in the northern part of Thailand can be a potential source of materials used in plant-based diets. The chemical composition, morphological, physicochemical, functional, pasting, and thermal properties differed among the varieties. A, DA-P, and DP flours displayed excellent thickening capacity and are suitable for use as plant-based thickeners, fat replacers, and texturizers. DD and DE exhibited low viscosity and resistance to disintegration induced by heat and shear and are suitable as materials for meat formulations, meat replacers, extenders, sausages, and other foods requiring high heat and a short cooking time. DA-W flour exhibits moderate physicochemical properties, rendering it versatile for a multitude of applications. The study expands the spectrum of high-fiber and protein-carbohydrate sources with particular characteristics and possible health advantages, which can be relevant for further applications in both the food and non-food industries.

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#### Ethics approval

This study did not include any human subjects or animal experiments.

#### Consent to participate

Not applicable.

#### Consent for publication

Not applicable.

#### CRedit authorship contribution statement

**Saranchanok Wonglek:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Chuchat Jaikaew:** Resources, Data curation. **Yukiharu Ogawa:** Writing – review & editing, Supervision, Resources. **Jaspreet Singh:** Writing – review & editing, Supervision. **Worawan Panpipat:** Writing – review & editing. **Natthawuddhi Donlao:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

#### Declaration of competing interest

The authors declare no conflict of interest. The foundations supported this study had no role in the study design, data collection, or analysis. The authors alone are responsible for the content and writing of this paper.

#### Data availability

Data will be made available on request.

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