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Characterization of arrowroot (*Maranta arundinacea*) starch as a potential starch source for the food industry

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ABSTRACT

Arrowroot is an underutilized tuber crop in Sri Lanka and the characterization of starch was done to identify its nutritional, physicochemical, and functional properties to evaluate its potential for use in the food industry. This study distinctly advances the field of arrowroot starch characterization by providing more characterization techniques for starch samples from Sri Lanka. Arrowroot starch colour was closely similar to colour of wheat flour indicating that the effect of colour is minimum when replacing wheat flour. Oval, spherical, and irregular globular shapes were the predominant starch granule shapes for arrowroot. The average length of starch granules was 44.99 ± 1.27 μm while the width of granules was 31.44 ± 0.58 μm. The least gelation concentration was 8.0% indicating its better gel-forming ability. The nutritional composition of arrowroot starch consisted of low crude protein (0.72 ± 0.02%), crude fat (0.26 ± 0.19%), and crude fiber (1.00 ± 0.09%) contents indicating the purity of starch. Sodium, Potassium, Calcium, Iron, and Zinc contents were 52.6 mg/kg, 4312.95 mg/kg, 382.67 mg/kg, 9.07 mg/kg, and 2.59 mg/kg, respectively. Results of flour densities demonstrated the potential of arrowroot starch to be used in the pharmaceutical industry. Arrowroot starch had high viscosity defining its potential as a thickener. The starch also had high swelling power and solubility indices while solubility was positively correlated with viscosity (0.679; $P > 0.05$). The low moisture absorbance indicates a longer shelf life of stored arrowroot starch. Onset temperature (T_o) of 75.02 °C, peak temperature (T_p) of 77.95 °C, and conclusion temperature (T_c) of 82.43 °C were resulted from DSC thermogram. Arrowroot was identified as an A-type starch from x-ray diffractometry and the FT-IR spectrum of arrowroot was identical to starch and presented the carbohydrate nature of starch. Thus, arrowroot starch has a high potential to be used in the food industry based on its functional properties.

1. Introduction

Starch is the primary source of carbohydrates in plants and an essential component of the human diet. The food industry uses it as a

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valuable ingredient for a variety of applications. The starch is found as a primary carbohydrate in the amyloplasts in storage organs such as seeds and tubers and in the leaf chloroplasts in higher plants. A limited number of crops are mainly used for starch production worldwide; the most significant of these are potato, cassava, maize, and wheat while smaller amounts are from sorghum, sweet potato, rice, arrowroot, sago, and mung beans.

Starch is primarily utilized in the diet as a source of high-calorie foods, also it is used in the production of food to impart various functional properties, such as gelling and pasting, thickening, water retention, and stabilization [1]. Based on the amylose/amylopectin ratio, fat ratio, protein content and the shape, structure, and size of the granules, starch is used in the food sector to get gelling ability, adhesion, higher viscosity, and ability to retrograde [2].

Two different forms of macromolecules, amylose, and amylopectin can be fractured from starch. The predominantly linear molecule with a molecular weight of 5×10^5 to 10^6 is amylose and it is made up of anhydroglucose units joined by α(1,4) connections. Amylopectin is a highly branched polymer composed of anhydroglucose units linked α(1,4), as well as 2–4% α(1,6) linked branches, and has a molecular weight of several million [3].

Amylose and amylopectin molecules are organized within starch granules which consist of crystalline and amorphous regions. Amylopectin molecules contain short chains that are organized into double helices. These helices have the ability to come together and create crystalline lamellae [4,5]. The remaining double helices and the crystallites form the semi-crystalline, the remaining part being called the amorphous region. This section comprises both amylose and elongated chains derived from amylopectin [4]. Evidence suggests that the starch granule is structured with alternating layers of semi-crystalline and amorphous regions [4,6]. Starch types are classified depending on their different types of crystallinity from X-ray diffraction like A, B, and C types according to their amylopectin branch length [7].

In some food applications, flour made from tuber and root starch can be used in place of wheat flour [8,9]. Cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), yams (*Dioscorea* spp.), and edible aroid plants (*Colocasia esculenta* and *Xanthosoma* spp.) are the main and most popular local root and tuber crops in Sri Lanka [10]. Arrowroot (*Maranta arundinacea*; Family: Marantacea) is a herbaceous, underutilized tuber crop possesses rhizomes that spread horizontally below the surface. The starch content in the rhizome of arrowroot varies depending on the plant's age, comprising around 20% and in this starch content, approximately 20–30% is composed of amylose [2]. As a soothing agent and treatment for digestive issues, arrowroot is commonly used in folk and Ayurvedic medicine in Sri Lanka and is locally called "Hulankeeriya" or "Aerukka." Due to its limited availability and time-consuming starch extraction process, The utilization of arrowroot in the food industry is limited and primarily restricted to dishes such as porridge, boiled rhizomes with grated coconut, and curry, but it is a gluten-free alternative to wheat flour that can be used in food preparations [11].

Recently, it was discovered that arrowroot starch could be used in baked goods, ice cream stabilizers, jellies, cakes, and infant food [2,12]. While the potential of this starch in food preparations has not been fully exploited. Due to its excellent digestibility, arrowroot is useful for infants, the elderly, patients with digestive issues, and those with celiac disease [1,13].

It is important to identify and characterize alternative starch sources that have not yet been completely utilized to address the rapidly growing consumer demand for starch-based products. This study aimed to assess the nutritional properties, physicochemical attributes, and functional characteristics of arrowroot, considering its potential as a flour source for the food sector in Sri Lanka.

2. Methodology

2.1. Sample collection

Arrowroot rhizomes were harvested from the plants which were at the harvesting stage. Sample collection was done from five provinces (Western, Southern, Uva, North-Western, Sabaragamuwa) in Sri Lanka. Three different geographical locations were selected for each province. For the western province rhizome sample collection was done from four different geographical locations. Total number of samples was sixteen. Starch extraction was done separately for each sample.

2.2. Arrowroot flour preparation

With a few minor modifications, arrowroot starch extraction was done by wet extraction [14]. The rhizomes of arrowroot were cleaned, sliced, and peeled. The slices were ground into a homogenous mass using tap water and arrowroot in a 1: 2 (w/v) ratio for 5 min in a high-speed stainless steel blender (Preethi MG-172 E, Preethi Electrical Appliances, India). The resulting slurry was passed through a double cotton cloth for filtration. Water was manually separated after flour sedimentation overnight. The resulting pellets were ground in a grinder after being oven dried in a dry oven (Memmert UN 160, Germany) for 8–10 h at 60 °C with air circulation. The extracted starch was packed in LDPE bags after being sieved (425 μm) and stored at – 18 °C before further analysis.

3. Physicochemical properties

3.1. Arrowroot starch yield

Starch yield was calculated according to equation (1) [1].

$$\underset{yield\ \%}{Flour} = \frac{Weight\ of extracted\ starch\ (g) \times 100}{Weight\ of\ raw\ rhizomes\ (g)} \quad (1)$$

3.2. Determination of pH

To prepare the slurry, 10 g of arrowroot starch was mixed with 15 ml of distilled water. The mixture was then heated, and additional distilled water was added to reach a total volume of 100 ml. After allowing the slurry to cool, the pH was measured using a benchtop pH meter (BP 300i, Trans Instruments) [15].

3.3. Flour colour

A colourimeter (PCE-CSM 2, PCE Instruments, United States) was used to assess the colour of arrowroot starch. The colourimeter was calibrated using the included calibration disc. Colour of the refined wheat flour was used as the standard. Colour of arrowroot starch samples were measured as samples with a comparison to colour of wheat flour (standard). The colour deviation of arrowroot starch samples from wheat flour was recorded as ΔE. The colour characteristics of L* (L* = 0 for black and L* = 100 for white), a* (-a for greenness and +a for redness), and b* (-b for blueness and +b for yellowness) were derived using the colour coordinates of L*a*b* values [11].

3.4. Starch granular morphology

To make the starch suspension, distilled water and glycerin were mixed (1:1 v/v) and then the starch was mixed with the solution mixture 1:1 (w/v). After staining the starch solution with a 1.0% iodine solution, a thin smear was created on a glass slide and covered with a coverslip. Images of starch granules were examined under a light microscope (OPTICA Microscope B-290, Italy) under ×40 and ×100 magnifications, and the shapes and sizes of starch granules were recorded. Images were captured and measurements were taken in micrometers (μm) using the Optica Pro View software [16]. Three replicates were done for each sample. Dry arrowroot starch was applied as a thin layer on an adhesive metallic surface for scanning electron microscopy (SEM), and gold was sputtered on top of it. A scanning electron microscope (SU 6600, HI-2108-003, Japan) operating at 5 kV was used to examine the metalized samples [17].

4. Nutritional properties

4.1. Proximate composition

The moisture content (%) of arrowroot starch samples was assessed using an infrared moisture analyzer (Kett FD-660, Kett, Japan). The total solid content was measured by subjecting the samples to drying in a dry heat oven at 105 °C for a duration of 3 h. The ash content was assessed using the muffle incineration method (at 540 °C), and the crude protein was quantified utilizing the Kjeldahl distillation method. A fiber analyzer (Fiber Extraction System F–6P, Spain) was used to quantify crude fiber. The crude fat content was assessed using the solvent extraction technique (Fat Extraction System SX-6 MP, Spain). All tests were carried out in accordance with the Association of Official Analytical Chemists' guidelines [18]. Total gross energy and total carbohydrate content were determined by calculations [19]. The dry ashing method was used to determine the minerals (Na, K, Ca, Fe, and Zn) [20]. The ash was dissolved in concentrated HCl, filtered, and diluted with distilled water to a volume of 50 ml. Atomic Absorption Spectrophotometer (GBC Avanta ver 1.33) and standards for elemental analysis were used to determine the mineral contents.

5. Functional properties

5.1. Least gelation concentration (LGC)

Using distilled water (5 ml), arrowroot starch suspensions (1–10% w/v) were prepared. The starch suspensions underwent thorough mixing for a duration of 5 min. Prepared flour suspensions were heated in test tubes for 30 min at 80 °C using a water bath before being subjected to rapid cooling under running tap water for 2 h. The sample that remained inside the inverted test tube was identified as having the lowest gelation concentration [21].

5.2. Moisture sorption capacity

Each starch sample was evenly spread out on petri dishes. These petri dishes were then placed inside a desiccator at room temperature with a relative humidity of 98% until a constant weight was attained. The samples were periodically weighed during this process. The moisture sorption capacity was calculated as the increment of weight as a percentage [22].

5.3. Flour densities

The flour densities were determined by following procedures [15]. Here occupied volume by a known mass of starch is measured.

Bulk Density: The bulk density (g/ml) of flour is the density determined without the influence of compression [23]. The process involved weighing 20 g of starch sample and depositing it into a glass graduated cylinder with a 100 ml capacity. Subsequently, the volume occupied by the flour was measured, and the weight of the flour was divided by the occupied volume.

Tapped Density: Tapped density is the flour density after applying mechanical compression. The volume of each drop was measured as a graduated cylinder carrying 20 g of flour when dropped 50 times from a height of 20 mm onto a bench.

Carr's Index: To determine the ratio, the difference between the tapped density and the bulk density was divided by the tapped density. The resulting value was then expressed as a percentage. This is used as the indicator for the compressibility of starch.

Hausner Ratio – The calculated value is obtained by dividing the tapped density by the bulk density. This indicates the flowability of starch.

5.4. Total starch content

The complete acid hydrolysis method was used to determine the starch content. A 2.5 g starch sample was mixed in a suspension containing 200 ml of distilled water and 20 ml of concentrated HCl. For 2.5 h, the mixture was heated in a flask equipped with a reflux condenser. After cooling, the contents were neutralized using 5 N NaOH, and the volume was adjusted to 250 ml. The resulting sugar, identified as dextrose, was quantified using the Lane and Eynon reducing sugar measurement method. To determine the starch content, the measured dextrose value was multiplied by 0.9 [24].

5.5. Amylose content

Arrowroot starch (100 mg) was mixed with 9 ml of 1 N NaOH and 1 ml of 95% (v/v) ethanol. The mixture was subjected to heating for 10 min and subsequently diluted to a final volume of 100 ml. Distilled water (50 ml), 1.5 ml of iodine solution, and 1 ml of 1 N acetic acid were mixed with 5 ml of the sample suspension. After the volume was raised to 100 ml and settled for 20 min, at 620 nm, the absorbance was measured by UV visible spectrophotometer (JENWAY 6305, Cole-Parmer Ltd, United Kingdom). The standard curve was generated using pure potato amylose [25].

5.5.1. Flour viscosity

The viscosity of arrowroot flour samples was assessed using a digital viscometer (VISCOTM-6800, ATAGO, Japan). To create a 10% starch suspension, arrowroot flour was mixed with distilled water and heated at 78 °C. The viscosity of flour suspensions was measured at 3-min intervals at 20 rpm [26].

5.6. Swelling power and solubility

Arrowroot starch (0.25 g) and 10 ml of distilled water were heated for 30 min at 78 °C while being constantly stirred before being centrifuged (FLC-04 S, Huangama Faithful Instrument, China) for 15 min at 3000 rpm. the slurry was cooled to room temperature. The starch sediment was measured after careful removal of the supernatant. The supernatant was transferred to a Petri dish that had already been pre-weighed, then it was evaporated for 2 h at 130 °C before being weighed [27]. The supernatant was dried, and the amount of starch that remained dissolved in water, as the residue, was determined. Equations (2) and (3) were used for the calculations.

$$Solubility\% = \frac{Wsp \times 100}{Ws} \tag{2}$$

where, Wss – weight of the soluble starch, Ws – weight of the sample, Wsp – weight of the sediment paste.

5.6.1. Differential Scanning Calorimetry (DSC)

DSC thermogram was obtained using Differential Scanning Calorimeter (Model DSC TA instrument Q 200, USA). A micro-syringe was used to add distilled water to the aluminum DSC pan. A 50% (w/w) mixture was prepared. Pan was sealed and kept at room temperature for 1 h. Readings were taken using an unoccupied pan as a reference. The scanning temperature extent and heating momentum were 20–100 °C and 5 °C/min, respectively [14]. Recorded temperatures included the peak temperature (Tp), onset temperature (To), and conclusion temperature (Tc).

5.7. X-ray diffractometry and FT-IR analysis

X-ray diffraction structures were observed using Bruker D8 Focus Diffractometer (Germany) equipped with EVA data analysis. The experimental conditions included Cu-Kα radiation (wavelength of 1.54 Å), a voltage of 40 kV, a current of 40 mA, 2θ range spanning from 5° to 90°, an increment of 0.02°, and a scan speed of 0.1 s/step. The transmission spectra between 3500 and 500 cm^{-1} were obtained using an FT-IR spectrophotometer (Nicolet 6700, USA) with 4 cm^{-1} resolution and 128 scans. Sample pellets were prepared by mixing 10 mg of vacuum-dried starch sample with 110 mg of fused KBr. Spectral analyses were conducted using OMNIC (version 8.0) software tools [28].

6. Experimental design and statistical analysis

The experimental design utilized in the study was the Completely Randomized Design (CRD). All measurements on starch properties were done in sixteen different samples which covered five different provinces in Sri Lanka. Mean values of five provinces were taken for the final analysis. The statistical analysis involving Analysis of Variance (ANOVA) and it was performed by MINITAB (version 19) software.

7. Results and discussion

7.1. Physicochemical properties

The arrowroot starch was a fine, white colour, odourless powder (Fig. 1. (d)) which was insoluble in water at room temperature (27 °C) and it was positive for the iodine starch identification test. Arrowroot rhizomes were obtained from plants (Fig. 1. (a)) that were at the harvesting stage. Rhizomes were cylindrical in shape, sympodial, white in colour and covered with scale leaves (Fig. 1. (b) (c)).

Arrowroot starch yield, pH of the starch suspensions, flour colour attributes and granular morphology indices are presented in Table 1. The starch production from root and tuber crops is reported to be 16–24% [29]. The average arrowroot rhizome comprises 20% of starch [2]. Innala (*Solenostemon rotundifolius*) tuber starch yield from wet extraction in Sri Lanka was determined to be 16% [30]. The yield of arrowroot starch in this study was 12.23 ± 0.62%. The rhizome of arrowroot is fibrous. Wet extraction of the starch removed a significant content of fiber, and as a result, the extracted starch percentage was low. According to previous studies, mechanical extraction methods which enhance the efficiency of wet extraction could produce higher starch yields of 16–20% for arrowroot [14,31–33]. Therefore, the development of a reliable machine assisted with wet extraction would be required for industrial

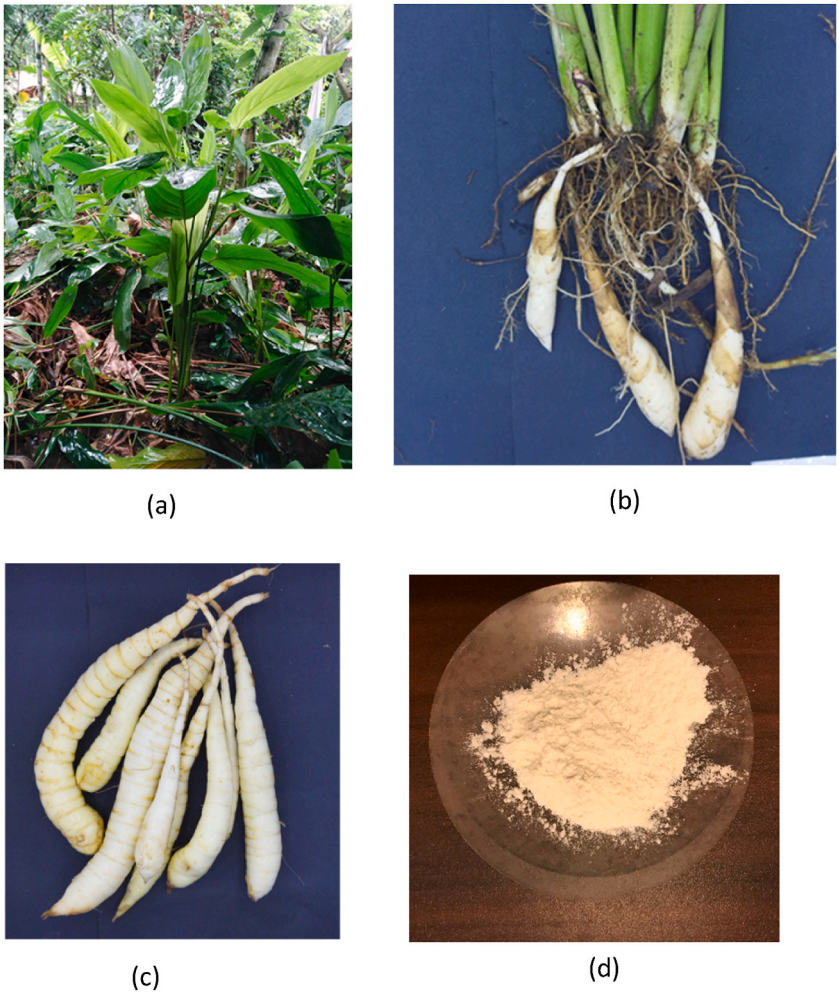

Fig. 1. (a) Arrowroot plant at harvesting stage (b) Formation of arrowroot rhizomes (c) Arrowroot rhizomes after removal of scale leaves (d) Arrowroot rhizome starch.

Table 1
Flour yield, flour colour attributes and granular morphology indices of arrowroot starch.

Parameter	Value
Starch yield (%)	12.23 ± 0.62
pH	7.03 ± 0.65
Colour attributes	
L*	92.92 ± 0.97
a*	1.17 ± 0.18
b*	7.22 ± 0.81
ΔE (when wheat flour is the standard)	4.12 ± 0.49
Granular morphology	
Oval shape (%)	49.54 ± 4.89
Spherical shape (%)	28.98 ± 2.53
Irregular globular shape (%)	21.48 ± 2.78
Length of the granule (μm)	44.99 ± 1.27
Width of the granule (μm)	31.44 ± 0.58
Least Gelation Concentration (LGC) (%)	8.00 ± 0.83

Mean ± SD; n = 5.

applications.

The pH value of arrowroot starch was 7.03 ± 0.65. Starch with pH of 3.0–9.0 is preferred for use in the pharmaceutical and food industries [34]. pH of 4.0 or less indicates fermentation and starch degradation and is unsuitable for food preparations [35]. Accordingly, the pH of arrowroot starch was at an acceptable level for food preparations.

Colour is one of the main organoleptic parameters which will describe the final quality and consumer perception of food products [36]. When arrowroot starch is used as a raw ingredient it will directly affect the appearance of finished food products. Since this study was conducted by taking the colour of wheat flour as the standard, it can measure the potential of arrowroot starch to replace wheat flour in food products considering colour. The arrowroot starch colour attributes were L* = 92.92 ± 0.97, a* = 1.17 ± 0.18, and b* = 7.22 ± 0.81. L* (lightness) indicates the brightness and the closeness of the flour colour to white whereas a* represents the redness and b* represents the yellowness of flour samples. Little a* and b* values indicate the little red and yellow tones of arrowroot starch samples [11]. ΔE is the colour difference of arrowroot starch from wheat flour (standard) and it was 4.12 ± 0.49. It provides evidence for the closeness of arrowroot starch colour to colour of wheat flour. A few studies done elsewhere have reported arrowroot starch

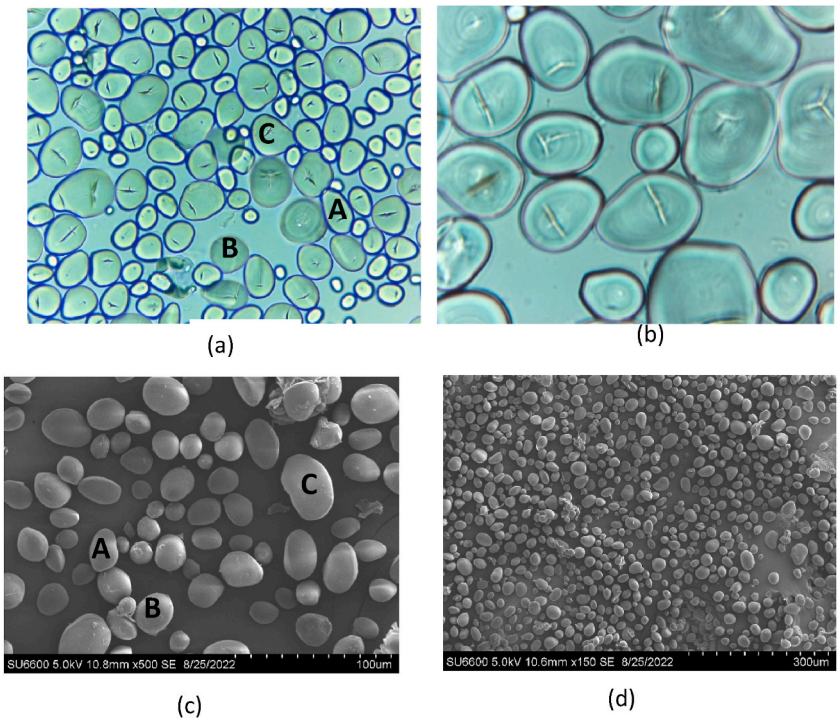

Fig. 2. Microscope images of the starch granules from arrowroot starch (A sample collected from western province) (a) Light micrograph (x40), (b) Light micrograph (x100), (c) and (d) Scanning electron microscope (SEM) images (A – spherical shape, B – Oval shape, C- Irregular globular shape).

colour attributes as L* = 75.50–80.10, a* = 1.02–2.61, b* = 8.96–11.61 [37], L* = 75.52, a* = 0.83, b* = 6.00 (in Brazil) [38] and L* = 87.5, a* = −1.24, b* = 6.61 [13]. Starch colour can be affected by the starch extraction method and the presence of macromolecules such as protein and fat [37]. L* values are increased when leaching of colour pigments during the starch isolation process and higher L* values enhance the potential of flour to be used in food applications [39].

Oval (49.54 ± 4.89%), spherical (28.98 ± 2.53%), and irregular globular (21.48 ± 2.78%) were the most prominent starch granule shapes (Fig. 2 (a-d)) present in arrowroot starch (Table 1). Circular, ovoid, bean-shaped, oval, spherical granules with smooth surfaces were observed in previous sudies [40,41]. The length and width of the starch granules were 44.99 ± 1.27 μm and 31.44 ± 0.58 μm, respectively. The starch granule surfaces were smooth due to the absence of fissures. As per previous studies, arrowroot starch granule width ranged between 20 and 40 μm [1,42] while in another study which was conducted in Brazil the average starch granule size was given as 56.60 μm [38]. Starch granular morphology can vary due to their botanical origins [43], biochemistry of chloroplast, plant physiology, and development stage of the plant [42,44]. Arrowroot starch granules are highly similar to starch from banana and potato [38].

8. Nutritional properties

The chemical composition of arrowroot starch can be found in Table 2. The moisture (%) of the starch was 10.87 ± 1.30% while the total solid content was 92.40 ± 1.31%. The moisture content of arrowroot starch was within the acceptable level (<15%) [45]. The ash contents of arrowroot starch (1.12 ± 0.13%) were comparable to previous studies (0.16–1.5%) [13,14,33,46,47]. The ash content of starches represents the available mineral compounds such as sodium, potassium, calcium, and, magnesium [48]. Lower ash content enhances the quality of starch due to the absence of inorganic matter but higher ash contents indicate better nutritional compositions [49]. Crude protein content and crude fat contents were 0.72 ± 0.02% and 0.26 ± 0.19%, respectively. Those values are close to the results reported in past studies for the crude protein content (0.4–0.8%) and crude fat content (0.12–1.0%) of arrowroot starch [13,14, 33,46,47,50]. Lower crude fat and protein levels indicate the purity and quality of the starch [14,48]. Root and tuber starches have low lipid and protein contents (<1.0%) [51]. Crude protein content of sweet potato, taro, yam, cassava, canna, and arrowroot were recorded as 0.50 ± 0.10, 0.60 ± 0.10, 0.60 ± 0.20, 0.40 ± 0.10, 0.80 ± 0.10, 0.60 ± 0.20%,respectively [9]. Chemical composition of arrowroot is comparable to cassava and potato starch [38].

Protein in starch produces a complex with surfaces of granules preventing the starch from expanding and resulting in reduced viscosity. Because starches are mostly utilized for thickening, this is disadvantageous. Fat and amylose can combine to produce a complex that slows down the gelatinization process by inhibiting the release of amylose from starch granules, and therefore, starch with a lower crude fat content is also considered to be of higher quality. Furthermore, fat will be taken up by the granule surface and produce a hydrophobic coating surrounding the granules. The ability to bind with water is reduced because of the fat layer [52].

The crude fiber content (1.00 ± 0.09%) was close to the crude fiber levels reported previously for arrowroot starch (i.e. 0.03–1.50%) from Philipines, Brazil, India, and Venezuela [13,33,46,53].

Comparatively, the amounts of potassium and calcium were higher than that of sodium, iron, and zinc. High phosphorus, sodium, magnesium, potassium, iron, zinc, and calcium content with stability during cooking are beneficial aspects of arrowroot from a nutritional standpoint [46]. However, very few investigations on the mineral content of various starches have been done [13].

9. Functional properties

9.1. Least gelation Concentration(LGC)

The Least Gelation Concentration (LGC) refers to the quantity of starch required to create the gel within a specified volume of water. This study resulted in the LGC of arrowroot starch as 8.00 ± 0.83%. LGC is an important factor in food preparations and it

Table 2
Proximate composition and minerals content of arrowroot starch.

Component	Value
Moisture (%)	10.87 ± 1.30
Total solid (%)	92.40 ± 1.31
Ash (%)	1.12 ± 0.13
Crude fat (%)	0.26 ± 0.19
Crude protein (%)	0.72 ± 0.02
Crude fiber (%)	1.00 ± 0.09
Carbohydrate (%)	88.70 ± 1.32
Energy (kcal/100 g)	359.66 ± 3.92
Sodium (mg/kg)	52.60
Potassium (mg/kg)	4312.95
Calcium (mg/kg)	382.67
Iron (mg/kg)	9.07
Zinc (mg/kg)	2.59

Mean ± SD; n = 5.

depends on the structural components of flour, such as protein, carbohydrates, and lipids [54]. The phosphate ester presents in glucose residue, length of chain, and α-1, 6 linkages residual are among the factors which affect LGC [55].

9.2. Flour densities, viscosity, swelling power, solubility, amylose content and total starch content

The results of flour densities, flour viscosity, swelling power and solubility, amylose content and total starch content are presented in Table 3.

The mean bulk density, tapped density, Carr's index, and Huasner ratio were 0.69 ± 0.01 g/ml, 0.88 ± 0.02 g/ml, 19.16 ± 1.86% and 1.24 ± 0.03, respectively. When the Carrs index exceeds 23% and the Hausner ratio exceeds 1.2, that starch does not have a good flow or compressibility. As per the results, Carr's index is at an acceptable level although the values of Hausner ratio have slightly exceeded the standard. Based on these properties, arrowroot starch is highly suitable to be used in the pharmaceutical industry [56].

The viscosity of arrowroot was 7660 ± 2910 cP and it indicates the better gel-forming ability of starch. The texture and integrity of the products are highly influenced by their viscosity. The viscosity depends on the flour processing method and starch interactions with hydrocolloids. When used as thickeners or stabilizers, flours with higher viscosities are appropriate. Due to its high viscosity arrowroot starch is beneficial as a potential food ingredient [57].

The amylose content of the arrowroot starch was 24.95 ± 1.49%. According to previous studies the total amylose content of arrowroot starch falls within the range of 16%–27% [50,51,58–61]. Flours are categorized based on the amylose content as, Low amylose (12–20%), intermediate amylose (20–24%), and high amylose (>24%). Based on the results of the current study, arrowroot was categorized as a "high amylose" flour. Food products from arrowroot flour could have a slightly higher stickiness and hardness [62]. The high amylose content of arrowroot starch allows for the production of films with enhanced technological properties, such as mechanical strength and barrier properties. These features make it a viable option for various applications such as biodegradable films and edible coatings.

The total starch content of arrowroot starch was 66.00 ± 0.48%. Total starch content represents the purity of starch. When the total starch content gets higher the starch is more purified and with lower content of impurities [48]. The results of this study revealed that crude fiber content is strongly negatively correlated with total starch content (−0.765; $P > 0.05$). The amount of fiber removal indicates the starch content and quality of the starch.

The swelling power of arrowroot starch was 11.22 ± 2.32 g/g. Swelling power is positively correlated with viscosity [63]. When the temperature increases, the swelling of starch granules increases and it indicates the strength of the internal forces of starch granules which maintains the granule structure [64]. When the temperature of the water is continuously increased, it causes the molecules in starch granules to vibrate vigorously, breaking the intermolecular hydrogen bonds in amorphous regions. As a result of swelling and partial solubilization, notably of amylose, water molecules establish hydrogen bonding connections with exposed hydroxyl groups of both amylose and amylopectin. This process leads to an increase in granule size [29]. The previously reported swelling powers of arrowroot starch were 11.32 ± 0.53 g/g [14], 11.58 ± 1.04 g/g [39] and 12.1 ± 0.08 g/g (at 80 °C) [13] and they were compatible with the results of the present study. Swelling power and solubility depends on the temperature factors such as molecular weight, amylose-amylopectin ratio, distribution of long chains, the degree of branching and conformation [48].

The solubility of arrowroot starch was 12.47 ± 1.62% at 78 °C. In past studies it has been recorded as 17.22 ± 0.96% at 90 °C [39] and 20.00% at 80 °C [46]. Increased swelling power and solubility observed in arrowroot starch result from the presence of a loose structure and low molecular weight of amylose [13]. This component leaches out from the amorphous region of starch granules, contributing to these properties. Solubility was positively correlated with viscosity (0.679; $P > 0.05$). Higher solubility is caused by the higher viscosity of arrowroot starch.

9.2.1. Moisture sorption capacity

Moisture absorption of arrowroot starch increased gradually with time (Fig. 3). A somewhat similar moisture absorption pattern was identified for Kithul (*Caryota urens*) starch [28]. It measures the absorbed atmospheric moisture which represents the amount of water-absorbing molecules in starch. The values indicate that arrowroot starch had low moisture sorption capacity. Starches with a

Table 3
Flour density, solubility, swelling power, viscosity, amylose content and total starch content of arrowroot starch.

Parameter	Value
Least Gelation Concentration (LGC) (%)	8.00 ± 0.83
Bulk density (g/ml)	0.69 ± 0.01
Tapped density (g/ml)	0.88 ± 0.02
Carr's Index (%)	19.16 ± 1.86
Hausner ratio	1.24 ± 0.03
Viscosity (cP)	7660 ± 2910
Swelling power (g/g)	11.22 ± 2.32
Solubility (%)	12.47 ± 1.62
Amylose content (%)	24.95 ± 1.49
Total starch content (%)	66.00 ± 0.48

Mean ± SD; n = 5.

high moisture sorption capacity exhibit a looser structure in the starch polymer, whereas starches with low moisture-sorption capacity tend to have a more compact structure. Starches with high moisture sorption capacity are easy to soften and digest but they tend to spoil faster [57].

9.2.2. Differential Scanning Calorimetry (DSC)

Results of Differential Scanning Calorimetry (DSC) had an observable endothermic peak. Onset temperature (T_o) = 75.02 °C, peak temperature (T_p) = 77.95 °C and conclusion temperature (T_c) = 82.43 °C (Fig. 4). When starch granules disintegrate, their internal structure is represented by the value of the onset temperature, which then reflects the release of polysaccharides into the surrounding media, and onset temperatures describe the stability of starch granules [39,63]. The phase of starch gelatinization occurs when the extraneous chains of amylopectin lost their double-helical crystalline structure [39]. A previous study [13] obtained a gelatinization temperature of 74.8 ± 0.34 °C while another study resulted T_o = 65.0 ± 1.40 °C, T_p = 72.5 ± 1.22 °C and T_c = 84.0 ± 1.13 °C for arrowroot in Indonesia [9]. In a study conducted in Brazil, low onset temperatures were recorded for cassava, arrowroot, and sweet potato (61.55 °C, 62.95 °C, and 62.85 °C, respectively) while yam and ginger recorded high onset temperatures [53]. A past study [46] recorded T_o = 67.75 °C, T_p = 73.62 °C, and T_c = 81.40 °C for arrowroot starch in Venezuela. Gelatinization temperatures indicate molecular orders or crystallinity, amylose content, amylopectin structure, and granule structure [38,39]. Lower gelatinization temperatures are beneficial in food preparations due to the reduction of time and heat during cooking [9].

9.2.3. X-ray diffractometry

X-ray diffractometer readings revealed the crystallinity and type of starch, based on their crystallinity. Starches are categorized into three different categories named A–type, B-type, and C-type based on their crystallinity. Starches that exhibit a prominent peak at approximately 5.6° 2θ alongside a broad peak at around 23° 2θ are categorized as B-type. On the other hand, starches demonstrating a strong double peak at approximately 17° and 18° 2θ are classified as A-type. C-type starches can be identified by broad peaks at roughly 17° and 23° 2θ, along with a few smaller peaks at 5.6° and 15° 2θ [39]. Results of X-ray diffractometry revealed that it belongs to Type A since it has two strong peaks around 17° and 18° (Fig. 5). All the observed diffractions peaks are at about 14°, 17.5°, 17.9° and 23° with interplanar spacing d = 5.94, d = 5.24, d = 4.98 and d = 3.89 nm. An intensity peak was observed at angle 2θ = 19.7° which is identical to starches with amylose-lipid complex. In past studies, it was observed arrowroot as a A-type of starch [39,41] (see Fig. 6).

However, another study [37] recorded a B-type diffraction pattern for arrowroot. The crystalline patterns of starches are influenced by factors such as the extraction process, growing conditions, and genotype [65]. In contrast to B-type starches, A-type starches exhibit a more compact arrangement in helical formations and contain a higher number of shorter branched chains per cluster. Gelatinized type-A starch is more digestible than gelatinized B-type starch [66]. The high digestibility of arrowroot starch may be impacted by this.

9.2.4. FT-IR analysis

Based on the findings from FT-IR analysis, the spectra of isolated arrowroot starch resulted in absorption bands between 576.99 and 926.97 cm^{-1} confirming the polysaccharide nature of starch. Hydroxyl groups play a crucial role as one of the primary functional groups in carbohydrates. They are responsible for both intra and intermolecular bonding through interactions with one hydroxyl groups [67]. The spectral region between 3000 and 3500 cm^{-1} displays a broad band with a peak at 3269.22 cm^{-1}, indicating complex vibration stretching associated with unbound intra and intermolecular hydroxyl groups [68]. The presence of a minor peak at 2926.31 cm^{-1} signifies the –CH stretching coupled with the ring methane hydrogen atoms.

The presence of the band at 1640.85 cm^{-1} is attributed to the twisting vibration of O–H in the bound water within the amorphous region of starch [38]. Angular twisting of CH_2 represents the band at 1335.05 cm^{-1} [69]. The sharp bands at 1149.33 cm^{-1} and 1077.07 cm^{-1} were due to the gathering of C–O, C–O–H bending and C–C stretching. The band at 926.97 cm^{-1} is caused by the sensitivity to water which defines the starch hydrophilicity [70]. The observed peaks within the range of 859.48 cm^{-1} to 1077.07 cm^{-1} are associated with different phenomena. The peak at 859.48 cm^{-1} results from hydrogen bonding of the O–H group, the peak at 1077.07 cm^{-1} corresponds to the vibration in the skeletal mode of α-1,4 glycosidic linkage, and the peak at an intermediate

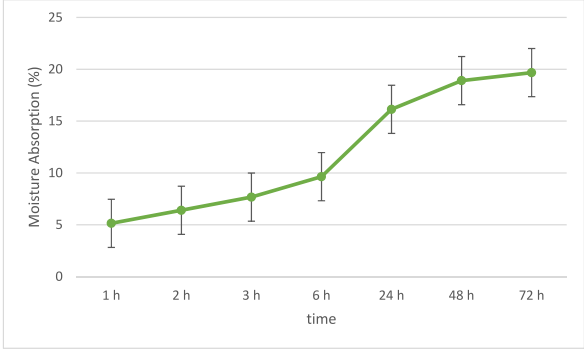

Fig. 3. Variation in moisture sorption of arrowroot starch with time.

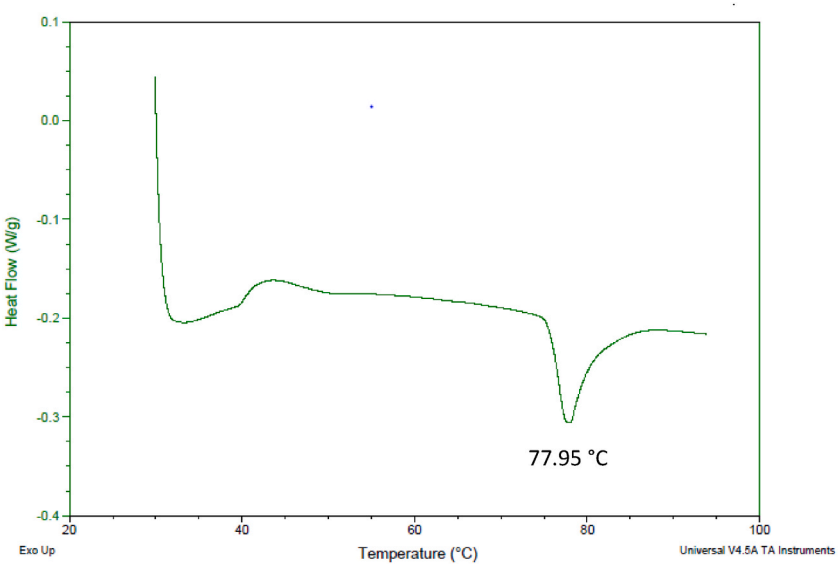

Fig. 4. DSC thermogram of arrowroot starch.

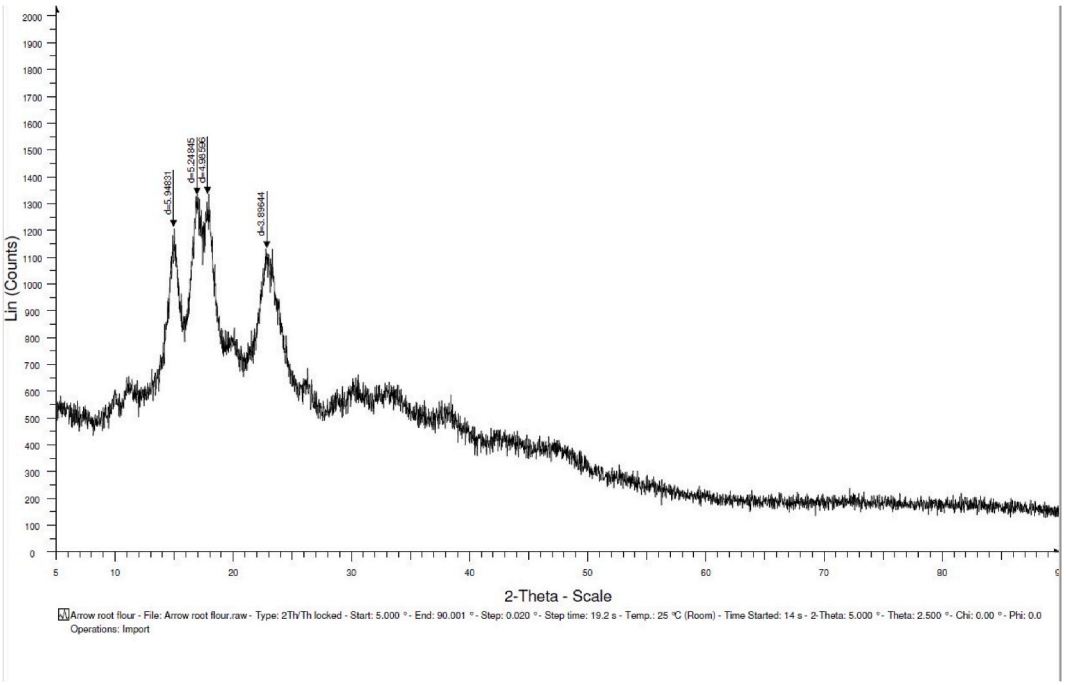

Fig. 5. X-ray diffraction pattern for arrowroot starch.

wavenumber is attributed to C–C stretching [69]. FT-IR spectrums have been identified for arrowroot starch previously were compatible with the result of this study [37,39].

10. Conclusion

Characterization of arrowroot starch for its chemical, physical and functional properties is essential to exploit this underutilized tuber crop as a potential starch source for the food industry. Introduction of a mechanically assisted starch extraction method will be more efficient for Sri Lanka. The starch colour of arrowroot is more similar to wheat flour (white). Oval, spherical, and irregular globular shapes were identified as the predominant starch granule shapes. Granule size was categorized as large by its dimensions. The

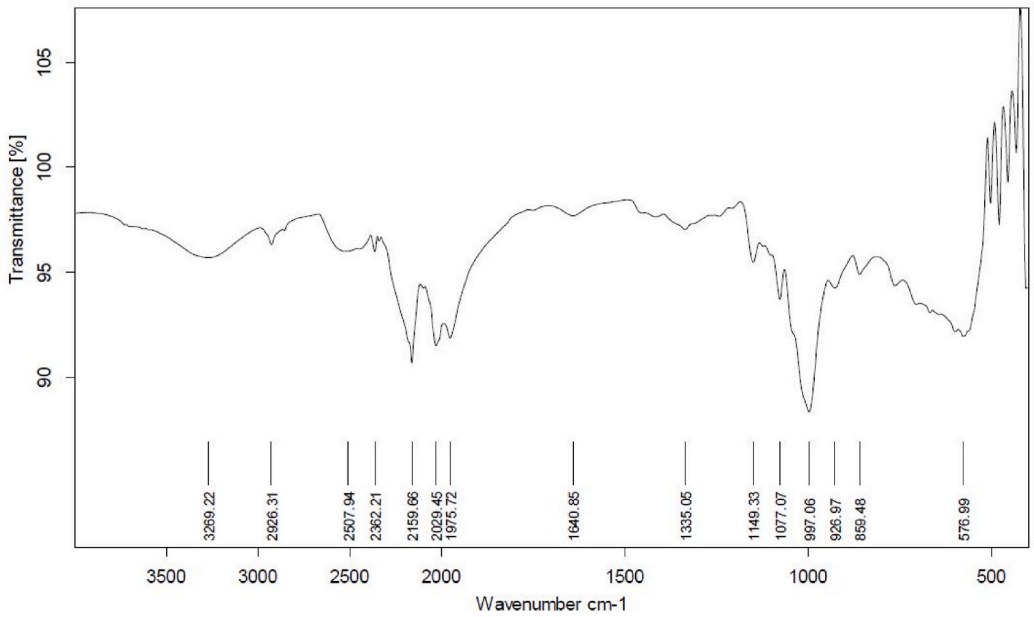

Fig. 6. FT-IR spectra of arrowroot starch.

least gelation concentration was 8.0%. Lower ash, crude fat, and crude protein contents were obtained with minor mineral composition indicating the identical composition for starches. Arrowroot was identified as a high amylose starch (24.95 ± 1.49%) indicating its potential to use in edible coating and film preparation. Arrowroot starch was identified as a starch with low moisture absorption capacity indicating a good shelf life. Onset temperature (T_o) = 75.02 °C, peak temperature (T_p) = 77.95 °C, and conclusion temperature (T_c) = 82.43 °C for arrowroot starch in Sri Lanka. Lower gelatinization temperatures are a characteristic of root and tuber starches. Arrowroot was identified as an A-type starch from this study and all the observed diffraction peaks were at about 14°, 17.5°, 17.9° and 23° with interplanar spacing d = 5.94, d = 5.24, d = 4.98, and d = 3.89 nm. FT-IR spectrum was identical to starch and confirmed the carbohydrate nature of arrowroot starch. This study consists of information about arrowroot starch to utilize it in the food industry and to identify the functional behavior, nutritional value, and physicochemical properties in food applications. These findings would provide useful information to utilize arrowroot starch for food innovations in Sri Lanka.

Complete ethics statement

Review and/or approval by an ethics committee was not needed for this study because there was no any involvement of human subjects or animals in this study.

Author contribution statement

M.K.S. Malki: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. J.A.A.C. Wijesinghe, R.H.M.K. Ratnayake, G.C. Thilakarathna: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

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.

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