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Morphological, physicochemical, and functional properties of 15 different dietary carbohydrate sources in Sri Lanka

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Abstract

Background: Carbohydrate is the primary source of energy in the human diet and plays an important role in a healthy diet. In this study, 15 different carbohydrate sources (white raw rice, red raw rice, white basmati rice, red basmati rice, wheat, atta flour, soy, black gram, corn, finger millet, water lily seeds, kithul, chickpea, oats, and palmyra sprouts) in Sri Lanka were investigated for their physicochemical and functional properties.

Results: The shape of the extracted starch granules varied according to the source, and the amylose content ranged from 17.22% to 36.12%. Kithul and black gram showed the highest water swelling capacity and water absorption index, respectively. Flour of white raw rice and finger millet showed significantly higher ($p < 0.05$) freeze–thaw stability than other sources. Flour of Soy, black gram, and chickpea showed significantly higher ($p < 0.05$) dietary fiber content and potassium content than other samples. Water lily seeds showed remarkable in vitro prebiotic activity from the studied carbohydrate sources.

Conclusion: The study indicates the potential utilization of raw white rice, palmyra, and finger millet starch in the food processing industry as alternatives to conventional starch sources. Furthermore, the flour from water lily seeds, white basmati rice, soy, and black gram has the potential for use in functional food preparation, offering a wide range of health benefits.

KEYWORDS
carbohydrate, dietary fiber, physicochemical properties, prebiotic activity, Sri Lanka

INTRODUCTION

Dietary carbohydrates play a significant role in developing type 2 diabetes and its associated health complications.[1,2] Systematic reviews and meta-analysis revealed that the type of carbohydrate (whole grain, refined grain, fruits, vegetables), their quality (glycemic index, glycemic load), and the composition (vitamin, minerals, dietary fiber, prebiotics content) critically influence the health.[3] In Sri Lanka, rice is the staple diet, and refined wheat flour is highly used in the bakery industry. The consumption of other carbohydrate sources is reported in lesser quantities. According to Jayawardana et al.,[4] Sri Lankans consume many starch servings; nearly 65% of adults consume well above the upper cutoff recommendation. It is widely believed that the high prevalence of diabetes in the country is closely associated with this dietary pattern. Although there are diverse starch sources in Sri Lanka, they remain underutilized with unknown properties.[5] Therefore, manipulating the main dietary component in the Sri Lankan diet, the carbohydrate portion, could be an excellent strategy to address the issues related to nutritional disorders.

This research compared the physicochemical and functional properties of commonly available 15 dietary carbohydrate sources in Sri Lanka. Four rice varieties (*Oryza sativa*)—red raw rice, white raw rice, white basmati rice, and red basmati rice—three legumes—Soy (*Glycine max*), black gram (*Vigna mungo*), and chickpea (*Cicer arietinum*)—several other kinds of cereals—oats (*Avena sativa*), finger millet (*Eleusine coracana*), corn (*Zea mays*), refined wheat flour, whole grain wheat flour (*Triticum aestivum*)—and some other sources—palmyra (*Borassus flabellifer*) sprouts, white water lily (*Nymphaea pubescens*) seeds, and kithul (*Caryota urens*—were selected for the study. Of these 15 sources, finger millet, palmyra, water lily seeds, black gram, and kithul have been identified as non-conventional and underutilized sources, which has a huge potential in various industrial applications.

There is an emerging trend to recognize new starch sources suitable for food and nonfood applications.[6–9] In addition, bioactive carbohydrates such as dietary fiber, prebiotics, and oligosaccharides are well-recognized for their health benefits.[10] Further, the prebiotic activity of the carbohydrate sources mentioned above is minimally discussed in the literature. Thus, this study provides a meaningful comparison between the available carbohydrate sources in Sri Lanka to explore the potential of utilization for industrial applications and functional food preparation.

MATERIALS AND METHODS

Chemicals

Heat stable α–amylase (A3306), amyloglucosidase (A9913), protease (P3910), celite acid washed (C8656), pancreatin (218411), and pepsin (77160-100G) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Freeze-dried probiotic culture of *Lactobacillus acidophilus* (LA-5) and *Bifidobacterium animalis* subsp. *lactis* (nu-Trish BB-12) were obtained from CHR HANSEN holdings A/S, Denmark. Culture media—Lactobacillus MRS agar, Modified Bifidobacterium agar, Peptone-bacteriological, and Lactobacillus MRS broth—were purchased from HiMedia Laboratories Pvt. Ltd. All other chemicals were in analytical grade and purchased from Sigma-Aldrich (St. Louis, USA) unless otherwise stated.

Sample collection and preparation

Fifteen different carbohydrate sources available in Sri Lanka were selected for the study. Fresh seeds and grains—corn-Ruvan, white water lilly seeds, black gram-Anurada, Soy-PB1, chickpea, and finger millet-Oshada—were purchased from the Palwehera seed farm, Dambulla, Sri Lanka. Kithul, wheat flour, and whole grain wheat/atta flour were obtained from a local market in Sri Lanka. Oats and rice varieties—white basmati rice, red basmati rice, white raw rice-nadu, and red raw rice-kekulu—were purchased from a local market. Palmyra sprouts were acquired from a household in Jaffna, where it is grown abundantly. Samples were oven-dried at 60°C and ground and sieved to separate the particles range in 100–150 μm.

Isolation of starch

Starches were extracted using the alkali method as described by Noor et al.[11] with slight modifications. Ground flour samples were soaked in 0.5% NaOH solution for 6 h at room temperature, with continuous agitation. The slurry was then filtered through a 100-mm mesh stainless sieve and allowed to settle overnight at 4°C. The supernatant was discarded, and the precipitate was washed three times with distilled water and then dried at 40°C for 24 h.

Starch granular morphology

Granular morphology of the isolated starch was observed using scanning electron microscopy (SEM) (EVO LS15, CarL Zeiss, Jena, Germany). Starch samples were applied on an aluminum stub using a double-sided adhesive tape and then coated with a thin film of gold. The images were recorded at ×10,000 magnification.

Determination of amylose content

The amylose content of the starch sources was determined using the Megazyme amylose/amylopectin assay kit (Megazyme Ireland International, Ltd.) by following the manufacturer's instructions. All analyses were carried out in duplicates.

Physicochemical properties

Freeze–thaw stability

Flour gel preparation was conducted according to the procedure described by Charoenrein et al.[12] with minor modifications. Briefly, flour suspension (9% w/w wet basis) was heated at 85°C for 25 min with interval agitation. Then, the samples were incubated at 25°C for 2 h and frozen at −18°C for 22 h. The samples were then thawed at room temperature for 2 h. Five freeze–thaw cycles were performed, and samples were centrifuged at 2200 rpm for 30 min. The syneresis of the freeze–thaw flour gel was measured as the percentage of water released after centrifugation.

Water swelling power and solubility index

Water swelling power (WSP) and solubility index (WSI) was performed according to the method described by Wani et al.[13] The 2% (w/v) starch dispersions were used for the analysis and transferred to a centrifugal tube. Then it was heated in a water bath at 90°C for 30 min.

Afterward, samples were cooled to room temperature and centrifuged at 3000 rpm for 15 min. Then the supernatant was separately collected into a pre-weighted Petri dish. The weight of the wet sediment was recorded, and the supernatant was dried at 110°C for 24 h.

Water absorption capacity

Water absorption capacity was determined according to Wani et al.[13] with minor modifications. The starch suspension (1/8 (w/v) in distilled water) was stirred for 30 min at room temperature and then centrifuged at 3000 g for 10 min. Afterward, the supernatant was separated, and the weight gain was expressed as water absorption capacity.

Determination of functional ingredients

Determination of dietary fiber composition

Dietary fiber contents were investigated using the enzymatic gravimetric method as previously described by Proskey et al.[14] specified in AOAC (2012)-991.43 using a dietary fiber assay kit (Sigma-Aldrich, TDF 100A-1KT). Duplicates were performed for each sample, and total dietary fiber (TDF) and insoluble dietary fiber (IDF) contents were assessed. The soluble dietary fiber (SDF) content was obtained by the difference between TDF and IDF fractions.

Quantification of mineral

The digestion was performed according to Sarikurkcu et al.[15] using a microwave-assistant closed vessel digestion system (MARS, CEM Corporation, North Carolina). Conditions for the microwave system were as follows: Ramping at 180°C for 15 min, holding at 180°C for 10 min, and cooling for 15 min. Duplicates were performed for each sample and analyzed for Ca, Mg, K, Na, Zn, Fe, Zn, Mn, and Cu by inductive coupled plasma-optical emission (ICP-OES) (iCPA 7000 series, Thermo Scientific). Multi-element standard solution 5 for ICP was used as the standard reference material for the calibration.

Determination of prebiotic activity

In vitro digestion of the starch sources

In vitro digestion was performed according to the procedure by Sayar et al.[16] with some modifications. Briefly, ground samples were digested with synthetic enzymes, α-amylase (5 mg/mL), pepsin (0.5 mg/mL), and pancreatin (0.5 mg/mL), sequentially at relevant pH and facilitated continuous agitation. Then the slurry was centrifuged, and the pellet (insoluble part) and supernatant were separately collected. The supernatant was then mixed with 95% ethanol four times and subjected to centrifugation again. Afterward, two pellets were collected and oven-dried at 50°C to obtain a fine powder.

Prebiotic activity assessment

The prebiotic effect was assessed by evaluating the proliferation of pure culture probiotic bacterial strains, *Bifidobacterium animalis* subsp. *lactis* (BB-12) and *Lactobacillus acidophilus* (LA-5), in the presence of 1% (W/V) of each in vitro digested starch substrate and glucose. The assay was performed according to the methodology reported by Huebner et al.[17] Bifidobacterium agar and Lactobacillus agar media were used for plating *B. animalis* and *L. acidophilus*, respectively. Plates having bacteria colonies within 25–250 were selected for calculations. Before statistical analysis, bacteria counts in the agar plates were transformed into $\log_{10}$ CFU/mL values.

Statistical analysis

A complete randomized design was conducted for both analyses. All data were statistically analyzed by one-way analysis of variance (ANOVA) using SAS software (SAS 9.3.1). Significant differences among means were separated by Duncan's multiple range tests. Differences at $p < 0.05$ were considered significant.

RESULTS AND DISCUSSION

Starch granular morphology

The granular morphology and size distribution in starch critically influence the physicochemical properties including swelling power, enzymatic digestibility, and water-holding capacity.[18] Morphological features of the extracted starch granules observed under the SEM are shown in Figure 1. Typical micrographs showed that the shape and size of starch granules differ according to the botanical source. The average area distribution of starch granules ranged from 12.22 to 1457.20 μm^2. Wheat and whole grain wheat flour showed spherical-shaped granules, while kithul showed both elongated and spherical granules. Rice starches—red raw rice, white raw rice, white basmati, and red basmati—and other cereal starches—finger millet and corn—showed polygonal-shaped granules. Legume starches—black gram and chickpea—showed elongated granules. Palmyra had both irregularly shaped large granules and small elongated granules. Kithul, chickpea, and black gram had comparatively larger granules, while rice starches had smaller granule sizes. The observed granule morphology of wheat, rice starches, and finger millet was in agreement with the previous reports by Chakraborty et al.[19] and Verma et al.[20]

Amylose content

Starch is composed of two glucose polymers: linear amylose and branched amylopectin. The ratio between amylose and amylopectin is accountable much for its functionality.[21] As given in Table 1, the amylose content in different dietary sources ranged from 17.22 to 36.12%. Palmyra had the highest amylose content, followed by whole grain

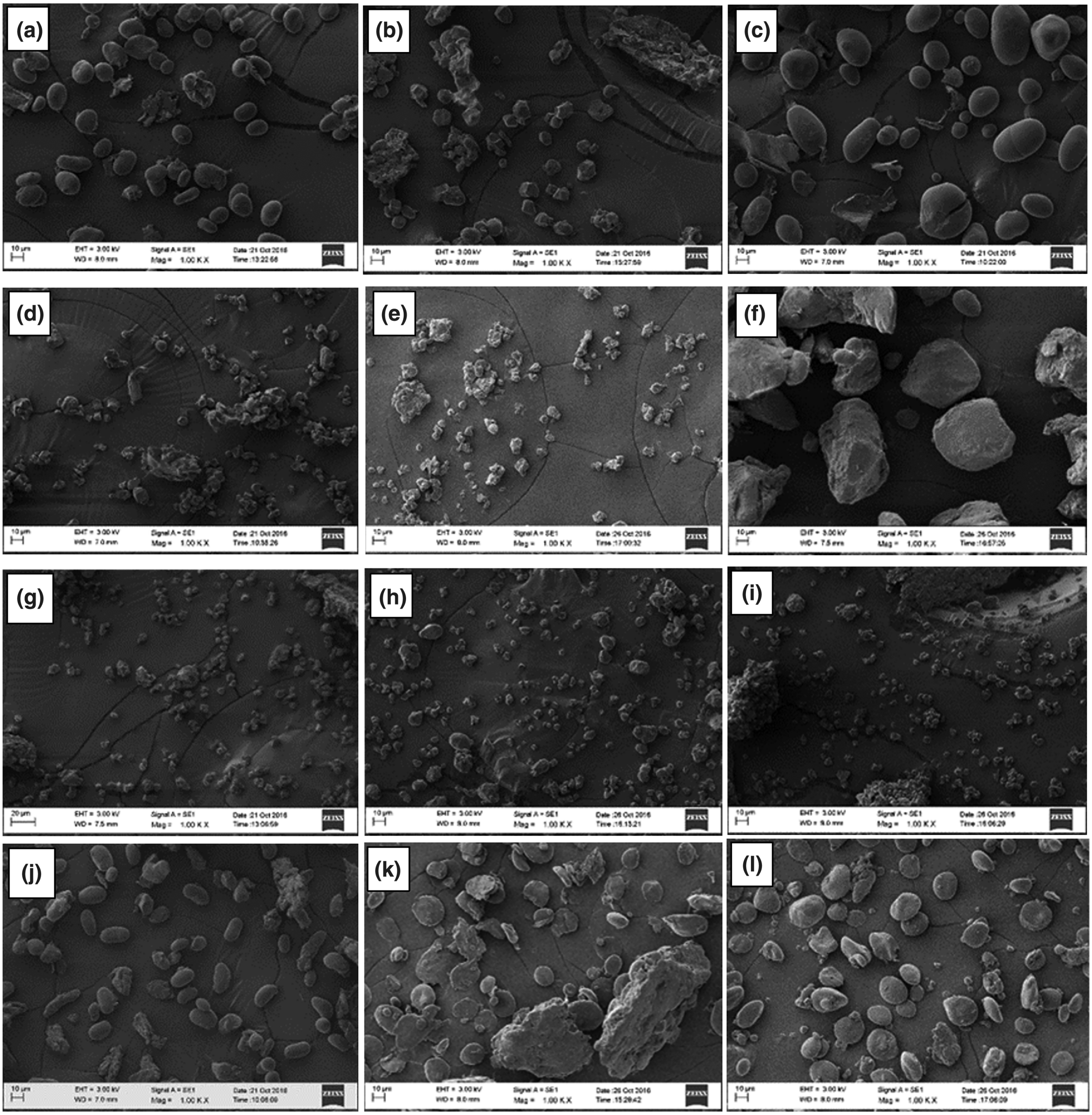

FIGURE 1 SEM images of starch isolated from (a) chickpea, (b) corn, (c) kithul, (d) finger millet, (e) oats, (f) palmyra, (g) red raw rice, (h) white raw rice, (i) white basmati rice, (j) black gram, (k) whole grain wheat flour, and (l) wheat flour.

wheat flour (33.45%) and black gram (32.95%). Soy showed the lowest amylose content of the studied samples. The amylose content in four rice varieties ranged from 19 to 31%. The obtained amylose content for the Soy, black gram, and wheat in this study complied with the findings by Stevenson et al.,[22] Singh et al.[23] and Soh et al.[24] respectively. However, the amylose content of finger millet was higher than the value reported in Jayawardana et al.[25] The discrepancies in amylose content could be related to the difference in variety, environmental factors, and the method employed for the determination.[26]

Water swelling capacity, water absorption index, and solubility index

Water swelling capacity (WSC) and water absorption index (WAI) are two important indices that estimate the suitability of a material for use as a stabilizer or binder. According to the data (Figure 2), kithul showed the highest WSC (13.2 g/g), followed by palmyra (11.82 g/g) and finger millet (10.42 g/g). Soy showed the least WSC (2.99 g/g) from the studied sample. Considering the WAI, black gram showed

TABLE 1 Syneresis% and amylose content in commonly consumed carbohydrate sources.

Starch sample	Syneresis (%)	Amylose (%)
Soybean	72.26 ± 2.08^{a}	17.22 ± 0.41^{k}
Black gram	24.25 ± 1.15^{g}	32.95 ± 0.86^{bc}
Chickpea	38.66 ± 1.15^{cd}	27.09 ± 0.32^{fg}
Oats	40.45 ± 3.34^{b}	25.41 ± 2.09^{i}
Finger millet	15.37 ± 0.52^{hi}	27.62 ± 0.93^{ef}
Corn	36.84 ± 1.60^{c}	31.83 ± 0.74^{cd}
Palmyra	17.05 ± 1.00^{h}	36.12 ± 0.92^{a}
Water lily seeds	23.53 ± 1.23^{g}	30.19 ± 1.48^{d}
Kithul	29.35 ± 1.24^{ef}	25.39 ± 0.65^{hi}
White raw rice	11.48 ± 0.81^{i}	26.07 ± 0.02^{gh}
Red raw rice	43.38 ± 1.10^{b}	30.95 ± 2.53^{e}
White Basmati	17.61 ± 0.48^{hi}	24.23 ± 0.98^{hi}
Red Basmati	23.54 ± 1.95^{g}	19.29 ± 0.21^{j}
Whole grain wheat Flour	31.05 ± 0.97^{de}	33.45 ± 1.10^{b}
Wheat	25.76 ± 4.32^{fg}	31.21 ± 0.49^{cd}

Note: Values are mean ± standard deviation. $n = 2$. Means with different superscript letters within a column are significantly different ($p < 0.05$).

the highest value (3.74 g/g), followed by palmyra (3.55 g/g), Soy (2.61 g/g), and finger millet (2.65 g/g). Wheat showed the lowest WAI among the studied samples. The discrepancies between WSC and WAI are associated with the different interactions of starch with cold water and hot water. Generally, starch is insoluble in cold water, and solubility occurs in hot water, where starch granules begin to swell rapidly only after the temperature reaches gelatinization temperature.[6] The solubility index of the starch sources varied from 44.20% to 6.53% (Figure 3), where the highest water solubility index was reported in Soy. Soy, chickpea, and corn showed a significantly ($p < 0.05$) higher solubility index than wheat flour.

According to the literature, the swelling factor of starch is greatly affected by the granule size, protein content, amylose content, and amylopectin-branched degree. Smaller granule size leads to higher water absorption due to the more elevated surface area-to-volume ratio.[24] Therefore, higher WSP is expected in starches with smaller granule sizes.[27] However, such a correlation could not be observed in the studied starch sources.

Freeze–thaw stability

Starch is used as an ingredient for producing frozen foods such as sausages, hams, surimi, and frozen batters. During long-term storage, these food products are typically exposed to a series of temperature fluctuations. Therefore, freeze–thaw stability in starch is an important factor in ensuring the textural quality of frozen products.[7,28] As shown in Table 1, Soy showed the highest syneresis percentage (72.26%), reflecting the lowest freeze–thaw stability. The lowest syneresis percentage was reported in white raw rice (11.48%), followed by finger millet (15.37%) and palmyra (17.05%). Wheat is the most commonly used starch source in the bakery industry, where its syneresis percentage was reported as 25.76% in the present study. In this experiment, white raw rice, finger millet, palmyra, and white basmati showed significantly ($p < 0.05$) lower syneresis percentage than wheat flour. It indicated higher freeze–thaw stability than wheat flour and would make them more desirable in industrial purposes.

Dietary fiber composition

Dietary fiber received considerable research interest as it exerts several physiological benefits by reducing the risk of cancer, type 2 diabetes, and cardiovascular disease.[29,30] The dietary fiber compositions of the selected starch sources are presented in Table 2. The TDF and IDF contents differed significantly ($p < 0.05$) among 15 starch sources. Soy flour showed the highest TDF, IDF, and SDF content, while wheat flour showed the lowest DF content. TDF and IDF values extended in a broad range: 2.31–38.70% DM, 2.05–32.75%, respectively, where SDF accounted for less than 6% of dry matter. Soybean, black gram, and chickpea flour, which belong to the legume family, showed significantly ($p < 0.05$) higher DF content than other sources. Out of cereal starch sources, Oats resulted in significantly ($p < 0.05$) higher TDF (17.38%) and IDF (12.48%) content. Water lily seed flour showed moderately higher TDF content (11.34%) and received the highest SDF/TDF ratio, followed by Oats and Kithul. The results were in accordance with the literature by Awika et al.[31] that confirmed higher dietary fiber content of legumes compared with cereals. Red raw rice and Red basmati rice flour showed significantly high dietary fiber content than White rice. Refined wheat flour had four times lower TDF content than Whole grain wheat flour. The reported DF content for Wheat flour was fairly agreed with the report by Thadhani et al.[32] The lowest dietary fiber content of Wheat flour is mainly attributed to the changes that occur in the milling processing.[33,34]

Soy, black gram, and oats had significantly higher ($p < 0.05$) SDF content than other studied starch sources. SDF is specifically related to the increase in the passage of bile acid, binding toxic compounds, and providing an excellent fermentable substrate to colon microorganisms.[35] Therefore, water lily seeds, oats, and kithul, like starch sources that have higher SDF/TDF, could exert high prebiotic activity.

Mineral composition

The mineral contents in the studied starch sources are presented in Table 3. According to the data, K, Ca, and Mg were the most abundant minerals in all studied starch sources. The potassium content varied from 608.6 to 7862.4 μg/g and magnesium content varied from 148–1099.1 μg/g. Soy had the highest level of K and the second highest level of Ca, Zn, and Mg. Selected legumes—Soybean, black gram, and chickpea—contained higher essential and trace elements than other starch sources. Corn had the highest Mg and Zn content, whereas water lily seed had the highest level of Na and Fe. Considering the rice

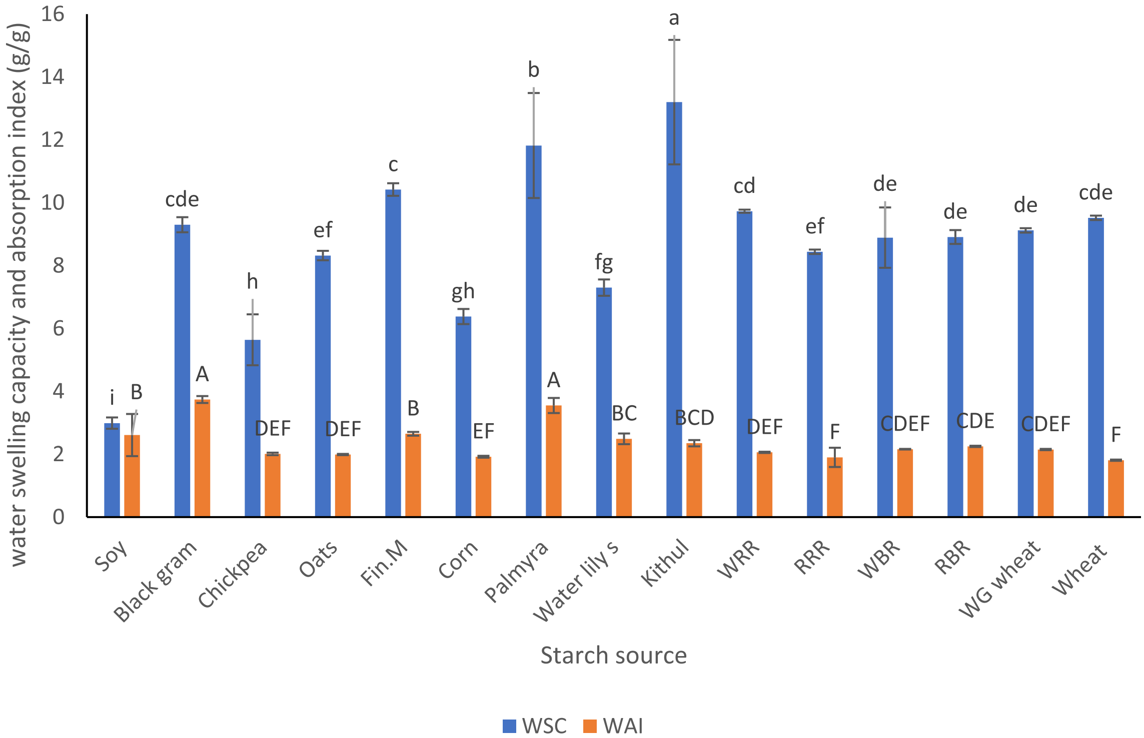

FIGURE 2 Water swelling capacity (WSC) and water absorption index (WAI) of starch sources. Values are given as means of three replicates ± SD. Mean difference in WSC and WAI is indicated in lowercase and uppercase letters, respectively; means with different superscript letters are significantly different ($p < 0.05$). Fin. M: Finger millet, WRR: White raw rice, RRR: Red raw rice, WBR: White basmati rice, RBR: Red basmati rice, WG wheat: Whole grain wheat flour.

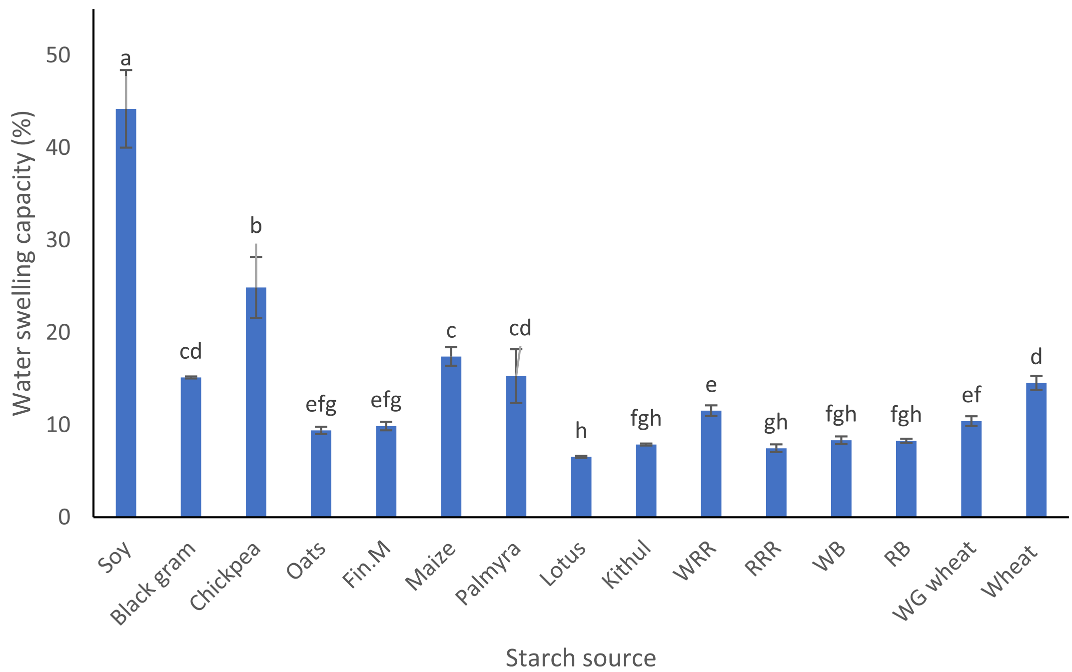

FIGURE 3 Water solubility index of starch sources. Values are given as means of three replicates ± SD. Means with different superscript letters are significantly different ($p < 0.05$). Fin. M: Finger millet, WRR: White raw rice, RRR: Red raw rice, WBR: White basmati rice, RBR: Red basmati rice, WG wheat: Whole grain wheat flour.

TABLE 2 Dietary fiber content (DF) of carbohydrate sources (dry matter basis).

Starch source	TDF content (%)	IDF content (%)	SDF content (%)	SDF/TDF content
Soybean	38.70 ± 0.24^{a}	32.75 ± 0.16^{a}	5.95 ± 0.07^{a}	0.15
Black gram	33.05 ± 0.13^{b}	27.44 ± 0.10^{b}	5.61 ± 0.03^{b}	0.17
Chickpea	22.91 ± 0.05^{c}	18.98 ± 0.07^{c}	3.93 ± 0.02^{d}	0.17
Oats	17.38 ± 0.14^{d}	12.48 ± 0.06^{d}	4.90 ± 0.20^{c}	0.28
Finger millet	15.51 ± 0.09^{e}	11.74 ± 0.18^{e}	3.12 ± 0.02^{f}	0.21
Corn	15.34 ± 0.32^{f}	13.41 ± 0.23^{f}	1.93 ± 0.09^{g}	0.14
Palmyra	11.82 ± 0.05^{g}	10.25 ± 0.15^{g}	1.57 ± 0.11^{h}	0.13
Water lily seeds	11.34 ± 0.11^{h}	8.02 ± 0.23^{h}	3.32 ± 0.12^{e}	0.29
Kithul	3.66 ± 0.15^{L}	2.73 ± 0.11^{L}	0.93 ± 0.03^{ij}	0.25
White raw rice	2.49 ± 0.10^{m}	1.93 ± 0.06^{n}	0.56 ± 0.04^{j}	0.22
Red raw rice	7.36 ± 0.18^{j}	6.39 ± 0.10^{j}	0.97 ± 0.07^{ij}	0.13
White Basmati	4.90 ± 0.13^{k}	3.82 ± 0.22^{k}	1.08 ± 0.08^{i}	0.22
Red Basmati	7.66 ± 0.19^{j}	7.31 ± 0.04^{i}	0.35 ± 0.15^{k}	0.04
Atta	8.48 ± 0.18^{i}	6.42 ± 0.07^{j}	2.06 ± 0.11^{g}	0.24
Wheat flour	2.31 ± 0.13^{m}	2.06 ± 0.09^{m}	0.25 ± 0.03^{k}	0.11

Note: Values are mean ± standard deviation. $n = 2$. Means with different superscript letters within a column are significantly different ($p < 0.05$).

TABLE 3 Mineral composition of commonly available carbohydrate sources.

Starch source	K	Ca	Mg	Na	Fe	Zn	Mn
Soybean	7862.4 ± 86.1^{a}	889.8 ± 0.8^{b}	992.0 ± 32.9^{b}	10.7 ± 0.5^{hi}	35.6 ± 0.4^{d}	20.7 ± 0.16^{b}	13.0 ± 0.1^{c}
Black gram	5806.3 ± 50.7^{b}	312.47 ± 8.6^{de}	807.7 ± 58.6^{c}	24.3 ± 0.2^{d}	23.2 ± 0.5^{f}	15.6 ± 0.2^{c}	7.6 ± 0.05^{g}
Chickpea	4828.1 ± 80.1^{c}	267.5 ± 69^{ef}	452.81 ± 9.6^{e}	32.1 ± 0.9^{c}	65.0 ± 1.6^{b}	14.3 ± 0.2^{d}	7.01 ± 0.05^{i}
Oats	2934.4 ± 19.7^{f}	257.5 ± 26.1^{ef}	183.14 ± 3.5^{fgh}	18.7 ± 1.1^{ef}	7.6 ± 0.2^{ijk}	6.5 ± 0.1^{i}	7.4 ± 0.1^{h}
Finger millet	1836.2 ± 51.1^{h}	729.1 ± 34.2^{c}	394.4 ± 7.5^{e}	18.5 ± 0.2^{ef}	10.2 ± 0.4^{hi}	5.6 ± 0.02^{j}	29.1 ± 0.03^{a}
Corn	4294.4 ± 7.6^{d}	125.5 ± 5.4^{ghi}	1099.1 ± 72.8^{a}	11.9 ± 0.3^{hi}	28.6 ± 0.9^{e}	25.1 ± 0.07^{a}	5.7 ± 0.1^{j}
Palmyra	3591.8 ± 58.2^{e}	166.7 ± 11.6^{gh}	162.6 ± 3.22^{gh}	59.6 ± 4.3^{b}	10.1 ± 0.68^{hij}	4.6 ± 0.0^{k}	2.2 ± 0.02^{n}
White waterlily	1531.7 ± 16.0^{i}	356.9 ± 5.57^{d}	276.3 ± 7.3^{f}	79.1 ± 2.3^{a}	119.6 ± 3.74^{a}	8.4 ± 0.02^{h}	11.81 ± 0.04^{d}
Kithul	1610.5 ± 30.5^{i}	1015.6 ± 34.4^{a}	600.2 ± 44.5^{d}	23.6 ± 0.3^{d}	59.2 ± 1.15^{c}	11.2 ± 0.3^{f}	9.3 ± 0.2^{f}
White raw rice	653.4 ± 24.6^{k}	42.8 ± 2.3^{j}	250.8 ± 2.11^{fg}	8.5 ± 0.5^{i}	4.4 ± 0.2^{k}	5.9 ± 0.12^{j}	5.08 ± 0.11^{k}
Red raw rice	1365.2 ± 27.2^{j}	75.19 ± 4.58^{ij}	666.93 ± 4.0^{d}	13.7 ± 0.5^{gh}	12.3 ± 0.6^{h}	9.5 ± 0.02^{g}	11.3 ± 0.03^{e}
White basmati	1325.7 ± 8.64^{j}	59.1 ± 1.9^{ij}	691.5 ± 7.1^{d}	16.9 ± 0.8^{fg}	6.7 ± 0.3^{jk}	5.65 ± 0.2^{j}	2.6 ± 0.1^{m}
Red basmati	2473.4 ± 26.2^{g}	122.72 ± 4.87^{ghi}	1034.4 ± 60.4^{ab}	22.23 ± 0.3^{de}	16.4 ± 0.2^{g}	13.5 ± 0.01^{e}	18.79 ± 0.2^{b}
Atta	1776.8 ± 41.1^{h}	196.6 ± 11.5^{fg}	445.21 ± 14^{e}	17.0 ± 0.5^{fg}	18.7 ± 0.5^{g}	10.8 ± 0.1^{f}	11.12 ± 0.4^{d}
Wheat flour	608.6 ± 13.57^{k}	118.4 ± 9.9^{hi}	148.3 ± 7.7^{h}	9.5 ± 0.2^{hi}	7.5 ± 0.2^{ijk}	4.7 ± 0.02^{k}	3.1 ± 0.13^{L}

Note: Values are mean ± standard deviation. $n = 2$. Means with different superscript letters within a column are significantly different ($p < 0.05$).

varieties, red raw rice and red basmati had significantly higher mineral concentrations than white raw rice and white basmati, showing that red rice varieties are nutritionally rich and healthier than the white rice varieties.[36] The values for the mineral composition in red rice and white rice fell in line with the results by Jiang et al.[37] In this experiment, wheat showed the lowest content of K, Mg, Zn, and Mn from the studied starch sources. Results depict the importance of the consumption of legumes, which is a good source of minerals compared with other starch sources. These findings would help in developing functional foods and various other value-added products.

Prebiotic activity

Prebiotics are defined as "non-digestible food ingredients that beneficially affect host health by selectively stimulating the growth and activity of one or a limited number of bacteria in the colon".[38] The higher number of beneficial bacteria in the colon leads to an increase in the nutrient and mineral absorption in the intestine, stimulates the production of short-chain fatty acids, and synthesis of water-soluble vitamins. Thus, there is an emerging trend of using prebiotics for functional food preparation.[39] The current study focused on evaluating

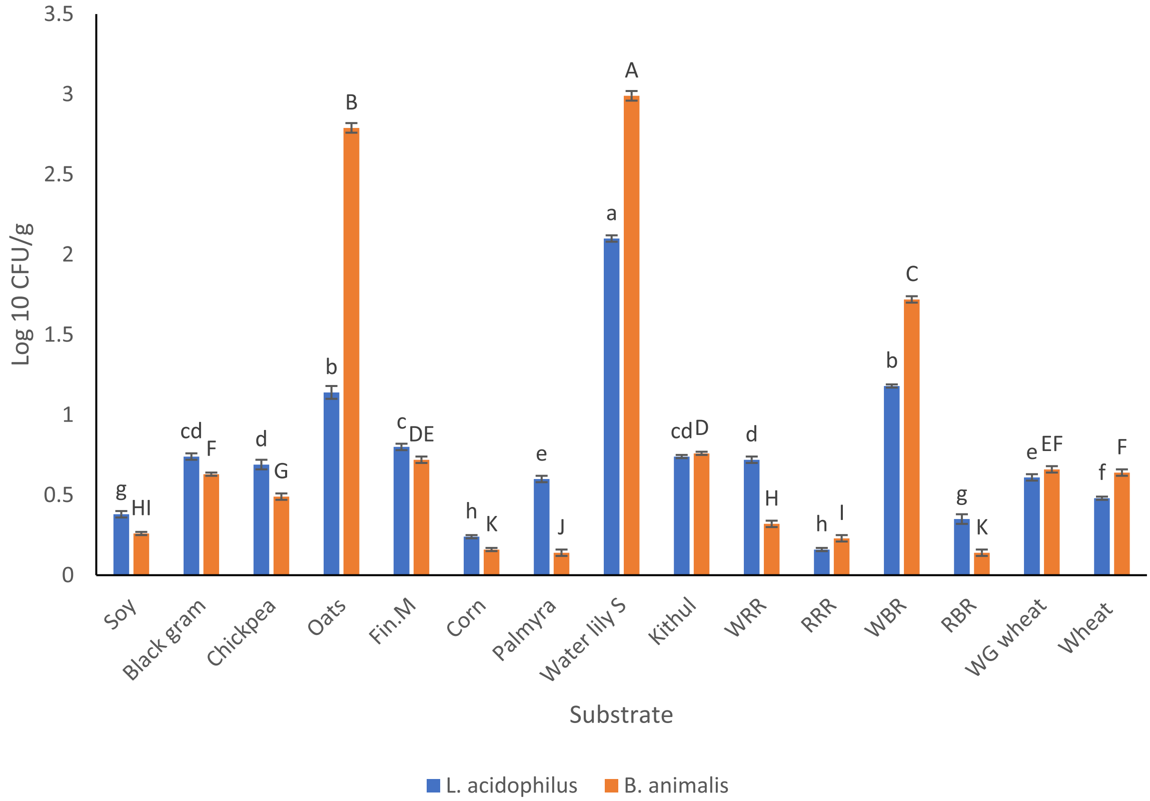

FIGURE 4 Effect of starch substrate on the proliferation of *Lactobacillus acidophilus* and *Bifidobacterium animalis* subsp. Lactis. Values are given as means of three replicates ± SD. Means with different superscript letters are significantly different ($p < 0.05$). Mean difference between bacterial count in *L. acidophilus* and *B. animalis* are expressed in lowercase and uppercase letters, respectively. Fin. M: Finger millet, WRR: White raw rice, RRR: Red raw rice, WBR: White basmati rice, RBR: Red basmati rice, WG wheat: Whole grain wheat flour.

the proliferation ability of probiotic bacteria: *Lactobacillus acidophilus* and *Bifidobacterium animalis* Sub sp. *lactis* in the presence of 15 different starch sources. The quantitative changes in the bacterial population at the end of the fermentation period are shown in Figure 4. For both strains, water lily seeds showed the highest bacterial growth enhancement. The media containing water lily seed, oats, and white basmati received significantly ($p < 0.05$) higher growth enhancement than all other carbohydrate substrates.

Finding supportive evidence is rare to prove the result obtained for the present study. Studies conducted so far mainly focused on assessing the prebiotic activity of purified oligosaccharides (fructo-oligosaccharides, galacto-oligosaccharides), inulin, lactulose, and resistant starch-like nondigestible compounds extracted from different dietary sources.[40–42] However, very limited studies have investigated the prebiotic activity using dietary sources without extracting these compounds. The data from those studies are also often based on one particular substrate or limited to two or three starch substrates.[43]

Several in vitro studies have specifically focused on evaluating the prebiotic effect of Lotus seed. It has been identified that Lotus seed is a rich source of bioactive compounds, water-soluble polysaccharides with a high content of oligosaccharides, and resistant starch,[44] which might be the reason for the higher proliferation effect of probiotic bacteria with the presence of water lily seeds. Oats received considerable attention in the field of research due to their protective functions against most diet-related noncommunicable diseases. This would be due to the presence of β-glucan. Several in vitro studies recommend oats as one of the best sources of β-glucan,[29] which is not a miracle to depict the high prebiotic activity of oats. Interestingly, water lily seeds resulted in 0.96 log-fold higher growth enhancement of *L. acidophilus* and 0.2 log-fold higher growth enhancement of *B. animalis* than the oats as a fermentative substrate.

Although white basmati, finger millet, and kithul gained significantly ($p < 0.05$) higher bacterial proliferation than other starch sources, less research interest was received for those starch sources as fermentative substrates. There was no correlation between total dietary fiber content and prebiotic activity in these 15 starch sources, which might be due to the high variability in the selected botanical source. However, the ratio of soluble dietary fiber content to the total dietary fiber content (SDF/TDF) positively correlated ($r = 0.62$) with the prebiotic activity.

CONCLUSION

The isolated starch from selected botanical sources exhibited variations in granular morphology and size, with a notable difference in amylose content ($p < 0.05$). Among these sources, kithul, palmyra, and finger millet showed significantly higher WSC and WAI, suggesting their potential as effective binders or stabilizers. White raw rice, finger millet, and palmyra showed significantly higher freeze–thaw stability compared with that of wheat, indicating their suitability as ingredients in frozen and cold storage food manufacturing. The results indicate the potential utilization of white raw rice, palmyra, and finger millet starch in the food processing industry as alternatives to conventional starch sources.

Moreover, the flours of Soy, black gram, and chickpea showed significantly higher ($p < 0.05$) potassium content, along with significantly higher TDF and IDF content. These attributes suggest potential health benefits in the prevention of noncommunicable diseases. Water lily seeds and white basmati rice flour exhibited remarkable prebiotic activity, indicating their potential in the development of functional food with enhanced health benefits.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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