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Divya Pujala
M.Sc. Food and Nutrition, PGRC, PJTAU, Rajendranagar, Hyderabad, Telangana, India

Dr. Janaki Srinath Puskuri
Assistant Professor, Department of Foods and Nutrition, College of Community Science, PJTAU, Saifabad, Hyderabad, Telangana, India

Dr. Kamalaja T
Head of the Department, Department of Foods and Nutrition, College of Community Science, PJTAU, Saifabad, Hyderabad, Telangana, India

Dr. Neela Rani R
Principal Scientist (Extension)& Unit Coordinator, AICRP on WIA, Post Graduate and Research Centre, PJTAU, Rajendranagar, Hyderabad, Telangana, India

Corresponding Author:
Divya Pujala
M.Sc. Food and Nutrition, PGRC, PJTAU, Rajendranagar, Hyderabad, Telangana, India

Effect of modern processing on resistant starch and digestible starch content of millet-based meals in comparison with rice-based meals

Divya Pujala, Janaki Srinath Puskuri, Kamalaja T and Neela Rani R

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Abstract
Resistant starch and digestible starch are key starch fractions influencing the glycaemic response and nutritional quality of cereal-based foods. The present study evaluated the resistant starch and digestible starch content of modern processed millet meals, namely foxtail millet, browntop millet, little millet, proso millet and Kodo millet, in comparison with rice meal prepared using the Telangana Sona variety (RNR 15048). Meals were standardized and prepared according to ICMR-NIN dietary guidelines (2024). Starch fractions were quantified using an enzymatic method and expressed as percentage on a dry weight basis.
Resistant starch content ranged from 2.98% to 3.82%, with foxtail millet recording the highest value followed by browntop millet. Among the modern processed cereal-based meals, resistant starch followed a descending trend as: Foxtail millet (3.82±0.007%) > Browntop millet (3.78±0.007%) > Little millet (3.18±0.006%) ≈ Proso millet (3.16±0.006%) > Kodo millet (2.98±0.006%) > Rice-Telangana Sona (2.66±0.005%).
Digestible starch content ranged from 54.3 to 70.6% among millet meals. The descending order for digestible starch was: Rice-Telangana Sona (81.2±0.162%) > Proso millet (70.6±0.141%) > Foxtail millet (69.5±0.139%) > Kodo millet (57.6±0.115%) > Little millet (56.8±0.113%) > Browntop millet (54.3±0.108%). Significant differences were observed among millet varieties ($p<0.05$). The findings indicate the nutritional potential of modern processed millet meals for improved starch quality.

Keywords: Resistant starch, digestible starch, modern processing, Telangana sona variety, starch digestibility

Introduction
Rice (*Oryza sativa* L.) is a primary staple food for a large proportion of the global population and serves as a major source of dietary carbohydrates. However, most commonly consumed polished rice varieties are characterized by high digestible starch content and rapid enzymatic hydrolysis, leading to elevated post-prandial glycaemic responses. In recent years, the development of rice varieties with improved starch quality has gained attention. Telangana Sona (RNR-15048) is a short-duration, super-fine grain rice variety and is reported to possess a relatively low glycaemic index compared to conventional white rice varieties, making it nutritionally superior for regular consumption (Chandra Mohan *et al.*, 2021) [7].
Millets are a group of small-seeded cereal grains that are traditionally consumed in many parts of Asia and Africa and are gaining renewed global attention due to their nutritional and functional properties. Compared to refined cereals, millets are rich in complex carbohydrates, dietary fibre, micronutrients and bioactive compounds, which contribute to their potential role in the prevention and management of life style related metabolic disorders such as obesity and type 2 diabetes mellitus (Chandrasekara and Shahidi, 2010) [6], (Saleh *et al.*, 2013) [12].
Starch is the predominant carbohydrate component of millets and exists in different fractions, primarily digestible starch and resistant starch. Digestible starch is rapidly hydrolysed by digestive enzymes in the small intestine, leading to increased post prandial glucose response, whereas resistant starch escapes digestion and undergoes fermentation in the colon, producing short-chain fatty acids that confer several physiological benefits (Sajilata *et al.*, 2006; Nugent, 2005) [13, 11].

The proportion of resistant starch in foods has been associated with improved insulin sensitivity, reduced glycaemic response and enhanced gut health (Englyst *et al.*, 2013) [8]

Processing methods play a crucial role in modifying starch structure and digestibility. Modern processing techniques involving controlled heating, gelatinisation and cooling can induce starch retrogradation, resulting in increasing formation of resistant starch and altered digestible starch fractions (Hoover *et al.*, 2010) [9]. In millets, variations in amylose content, granule size and the presence of dietary fibre and polyphenols further influence enzymatic starch hydrolysis. Studies have reported that millets such as foxtail, Browntop and proso millet exhibit comparatively higher resistant starch and lower digestible starch content than conventional refined cereals, highlighting their functional advantage. (Annor *et al.*, 2014; Shobana *et al.*, 2022) [2, 15].

Despite the availability of low-glycaemic rice varieties such as Telangana Sona, comparative information on resistant starch and digestible starch content of modern processed millet-based meals in relation to rice-based meals remains limited. Therefore, the present study was undertaken to evaluate and compare the resistant starch and digestible starch content of selected modern processed millet meals proso millet, kodo millet, browntop millet, little millet and foxtail millet with modern processed Telangana Sona rice meal, to better understand differences in starch quality and nutritional potential.

Materials and Methods

Locale of the study

The present study was carried out at the Department of Foods and Nutrition, Post Graduate and Research Centre (PG&RC), Professor Jayashankar Telangana Agricultural University (PJTAU), Rajendranagar, Hyderabad, Telangana, India. All laboratory analyses, including moisture, fat, resistant starch and digestible starch estimation of modern processed millet meal samples, were conducted in the departmental food analysis laboratory under controlled conditions.

Procurement of Materials

Modern processed millet grains namely foxtail millet (*Setaria italica*), browntop millet (*Brachiaria ramosa*), little millet (*Panicum sumatrense*), proso millet (*Panicum miliaceum*) and Kodo millet (*Paspalum scrobiculatum*) were procured from reliable commercial retail outlet (Suraj Millet stores) in Kukatpally, Hyderabad, Telangana, India. All millet samples were obtained from the same batch to minimize variability. The grains were cleaned manually to remove foreign matter, packed in airtight containers and stored under ambient laboratory conditions until further analysis.

Preparation of Samples for Analysis

Modern processed rice (Telangana Sona, RNR 15048) and millet-based meals were prepared in accordance with the ICMR-NIN dietary guidelines (2024) to represent a standardized balanced meal. Each test meal consisted of 75 g raw cereal (rice or millet) as the primary component, accompanied by 30 g raw dal, 100 g non-starchy vegetable curry(bendi/Okra), 50 g green leafy vegetable, 150 mL curd, and 100 g fresh guava, while 10 g cooking oil was used uniformly for meal preparation. All ingredients were cooked using standard household methods under controlled conditions, and total cooking time was maintained within 40 minutes to ensure uniformity across samples.

After cooking, the meal components were thoroughly mixed to obtain a homogeneous composite meal. The prepared meals were allowed to cool to room temperature and then subjected to analytical procedures. A portion of each freshly prepared meal was immediately used for moisture estimation, followed by drying and grinding for fat analysis, resistant starch (RS) and digestible starch (DS) estimation. This approach ensured minimal compositional variation and reflected realistic dietary consumption patterns.

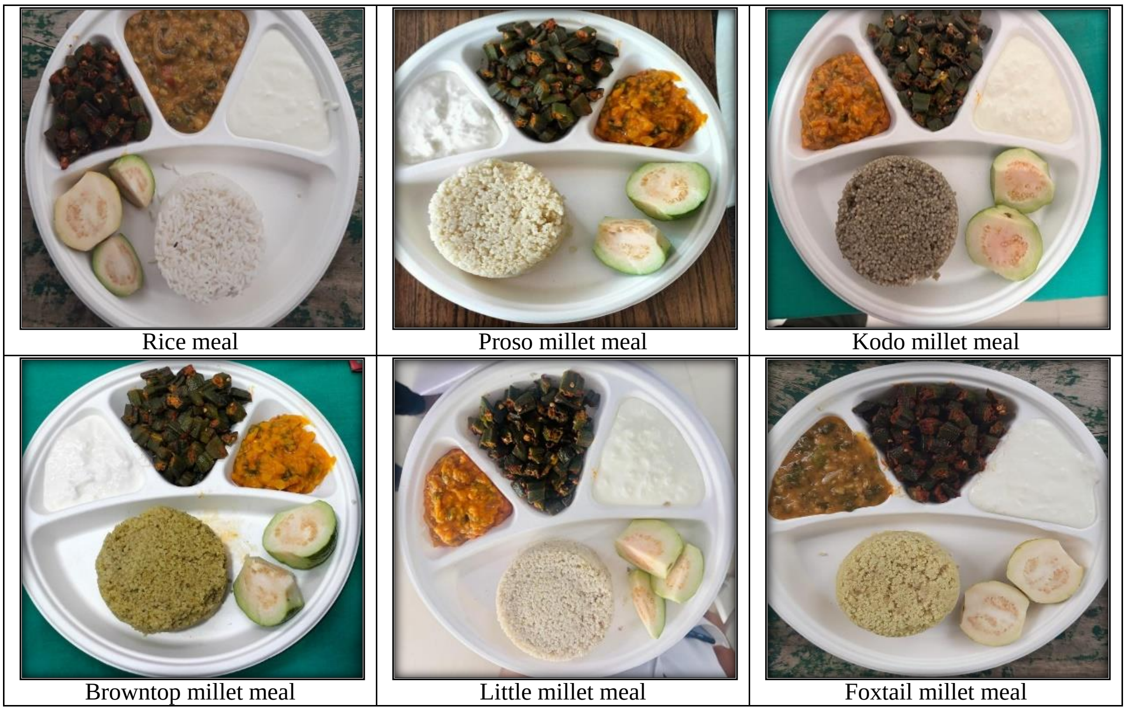

Fig 1: Standardized modern processed rice-based and millet-based meals prepared as per ICMR-NIN dietary guidelines (2024) for resistant starch and digestible starch analysis

Estimation of Moisture Content

Moisture content of the millet meal samples was determined according to AOAC (2016) [4] hot air oven method and expressed as percentage.

Approximately 10 g of each sample was weighed into a pre-weighed petri dish and dried in a hot air oven at 105 °C until constant weight was obtained. The dried samples were cooled in a desiccator and reweighed. Moisture content was calculated using the formula:

$$\text{Moisture (\%)} = [(W_2 - W_3)/(W_2 - W_1)] \times 100$$

Where:
W_1 = weight of empty petri dish (g)
W_2 = weight of petri dish with sample before drying (g)
W_3 = weight of petri dish with sample after drying (g)

Estimation of Fat Content

Crude fat content was estimated as ether extract using an automatic Soxtherm extraction unit following AOAC (2005) [3] method.

Approximately 4.0 g of moisture-free sample was placed in a thimble and extracted with petroleum ether (boiling point 60-80 °C) for about 1.5 h. After extraction, the solvent was evaporated and the extraction flask containing fat residue was dried in a hot air oven at 100 °C, cooled in a desiccator and weighed. Fat content was calculated as:

$$\text{Fat (\%)} = [(W_2 - W_1)/\text{Weight of sample}] \times 100$$

Where:
W_1 = weight of empty extraction flask (g)
W_2 = weight of flask after extraction (g)

Estimation of Resistant Starch and Digestible Starch

Resistant starch (RS) and digestible starch (DS) contents were determined using an enzymatic method with a commercially available Megazyme Resistant Starch Assay Kit, following AOAC Method 2002.02/AACC Method 32-40.01.

Approximately 100±5 mg of accurately weighed millet meal sample was incubated with pancreatic α-amylase and amyloglucosidase at 37 °C for 16 h with continuous agitation to hydrolyse digestible starch. The reaction was terminated by adding ethanol, followed by centrifugation. The supernatant containing digestible starch fractions was collected, while the pellet represented resistant starch.

The resistant starch pellet was solubilized using 2 M potassium hydroxide under ice-cold conditions, neutralized with sodium acetate buffer and hydrolyzed with amyloglucosidase. Glucose released from both digestible starch and resistant starch fractions was quantified using the glucose oxidase-peroxidase (GOPOD) reagent. Absorbance was measured at 510 nm using a spectrophotometer. Results were expressed as percentage on a dry weight basis.

Resistant starch (RS) and digestible starch (DS) contents were calculated according to the assay kit instructions and expressed as percentage on a dry weight basis, using the following equations:

- $\text{RS (\%)} = (\Delta E \times F/W) \times 90$
- $\text{DS (\%)} = (\Delta E \times F/W) \times 90$

For samples containing less than 10% resistant starch, a correction factor of 9.27 was applied.

Where ΔE is the absorbance difference between sample and blank, F is the factor obtained from the glucose standard, and W is the sample weight (mg).

Statistical Analysis

All analyses were carried out in triplicate, and results were expressed as mean±standard deviation. Data were subjected to one-way analysis of variance (ANOVA) to test for significant differences among millet varieties. Differences were considered statistically significant at $p<0.05$. Statistical analysis was performed using standard statistical software.

Results

The resistant starch (RS) and digestible starch (DS) contents of modern processed millet meal samples are presented in Table 1. Significant differences were observed among the millet varieties for both resistant starch and digestible starch contents ($p<0.05$).

Among the modern processed millet meals, resistant starch content ranged from 2.98 to 3.82%.

Foxtail millet recorded the highest resistant starch content (3.82±0.007%), followed closely by browntop millet (3.78±0.007%), little millet (3.18±0.006%) and proso millet (3.16±0.006%) exhibited moderate resistant starch levels, while Kodo millet recorded the lowest resistant starch levels (2.98±0.006%).

Modern processed rice (Telangana Sona) recorded a significantly lower resistant starch content (2.66±0.005%) compared to all millet meal samples. The differences in resistant starch content among millets as well as between millets and rice were statistically significant ($p<0.05$).

Digestible starch content of modern processed millet meals ranged from 54.3 to 70.6%, whereas rice exhibited a markedly higher digestible starch content.

Among the millet meals, proso millet recorded the highest digestible starch content (70.6±0.141%), followed by foxtail millet (69.5±0.139%). Little millet (56.8±0.113%) and Kodo millet (57.6±0.115%) showed comparatively lower digestible starch values, while browntop millet recorded the lowest digestible starch content (54.3±0.108%). Statistical analysis indicated significant variation in digestible starch content among the millet varieties ($p<0.05$).

Overall, foxtail and browntop millets demonstrated higher resistant starch content, whereas proso and foxtail millets exhibited higher digestible starch content among the modern processed millet meals. In contrast, rice (Telangana Sona) showed lower resistant starch and substantially higher digestible starch content, highlighting clear differences in starch fraction composition between millet-based and rice-based meals.

Table 1: Mean values of resistant starch and digestible starch content of modern processed millet-based meals and rice-based meals

Variety	Starch	Modern processed
Kodo Millet	RS	2.98^{a}±0.006
	DS	57.6^{a}±0.115
Proso Millet	RS	3.16^{b}±0.006
	DS	70.6^{b}±0.141
Browntop Millet	RS	3.78^{c}±0.007
	DS	54.3^{a}±0.108
Little Millet	RS	3.18^{b}±0.006
	DS	56.8^{a}±0.113
Foxtail Millet	RS	3.82^{c}±0.007
	DS	69.5^{b}±0.139
Rice	RS	2.66^{d}±0.005
	DS	81.2^{c}±0.162
F Value	RS	61001.16
	DS	14330.35
P value	RS	0.00*
	DS	0.00*

Note: Values are expressed as mean±standard deviation.

Discussion

The observed variation in resistant starch and digestible starch content among modern processed millet meals can be attributed to differences in starch composition, amylose content, starch granule structure, and the influence of processing on starch retrogradation. The higher resistant starch content recorded in foxtail and browntop millets may be associated with their relatively higher amylose content and a greater tendency for starch retrogradation during modern processing, which enhances the formation of enzyme-resistant starch fractions. Similar ranges of resistant starch in processed millet foods have been reported earlier, emphasizing the role of processing-induced structural reorganization of starch polymers (Sajilata *et al.,* 2006; Annor *et al.,* 2014) [13, 2].

The comparatively lower resistant starch content observed in kodo millet may be attributed to varietal differences in starch architecture and a reduced capacity for retrogradation. Digestible starch content was highest in proso and foxtail millets, indicating greater enzymatic accessibility of starch granules. In contrast, browntop millet exhibited the lowest digestible starch content, which may be due to the presence of higher dietary fibre, polyphenolic compounds, and a more compact starch granule structure that limits enzymatic hydrolysis. Earlier studies have similarly reported reduced starch digestibility in browntop and kodo millets owing to the inhibitory effects of non-starch components on digestive enzymes (Sharma *et al.,* 2008; Chandrasekara and Shahidi, 2010) [14, 6].

Modern processing techniques involving controlled heating and cooling are known to modify starch digestibility by promoting gelatinisation followed by retrogradation, thereby increasing resistant starch formation while reducing digestible starch fractions (Hoover *et al.,* 2010) [9]. The findings of the present study are in agreement with these observations and demonstrate that modern processed millet meals possess favourable starch characteristics. The relatively higher resistant starch and lower digestible starch content observed in certain millet varieties support their potential role in modulating glycaemic response and enhancing nutritional quality.

Conclusion

The present study demonstrated significant variation in resistant starch and digestible starch content among modern processed millet meal samples. Foxtail and browntop millets exhibited higher resistant starch content, while proso and foxtail millets recorded comparatively higher digestible starch values. Browntop millet consistently showed lower digestible starch content, indicating reduced starch digestibility.

These variations among millet varieties highlight the influence of inherent grain characteristics and modern processing on starch fractions. The relatively higher resistant starch and lower digestible starch content observed in certain millets underscore their nutritional advantage and improved starch quality. Overall, the findings support the inclusion of modern processed millet meals as functional carbohydrate sources with favourable starch digestibility characteristics when compared to conventional cereal-based foods.

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