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Quality characterization, optimization and consumer acceptance of enriched gluten-free crackers through valorization of chayote tuber and sprouted paheli dal flour

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Background: With rising awareness about gluten intolerance and the growing preference for healthier snack options, there is an increasing focus on developing gluten-free bakery products using nutrient-dense alternative flours. Among these, sprouted paheli dal flour (SPDF) and chayote tuber flour (CTF) stand out as promising ingredients because of their richness in protein, fiber, and essential micronutrients. *Objective*: The present study aimed to formulate and optimize gluten-free crackers using composite flours made from SPDF and CTF, and to evaluate their functional, nutritional, and physicochemical properties. *Methods*: Twelve different flour blends were prepared by varying the proportions of SPDF and CTF (70 : 30, 65 : 35, 60 : 40, 55 : 45, and 50 : 50) following a simplex lattice mixture design. The blends were analyzed for water and oil absorption capacities, foaming ability, and other functional characteristics. The best cracker formulation was identified using Design Expert software, and its proximate composition, acid-insoluble ash, and fat acidity were determined. *Results*: The composite flours showed good functional performance, with water absorption capacities ranging from 86.33% to 110% and oil absorption capacities between 97.33% and 144.33%. Foaming ability improved compared to refined wheat flour. The optimized formulation, containing 61.22% CTF and 38.78% SPDF, resulted in crackers with 3.72% moisture, 2.7% ash, 11.53% fat, 2.3% fiber, 15.78% protein, and 63.97% carbohydrates. Acid-insoluble ash and fat acidity were 0.032% and 1.12% oleic acid, respectively. Overall, the developed crackers had 58% more protein, 77% higher fiber, and nearly three times the vitamin and mineral content of refined wheat flour crackers. *Conclusion*: The combination of sprouted paheli dal and chayote tuber flour proved effective in creating a nutritious and gluten-free cracker with improved functional qualities. These findings highlight the potential of using underutilized crops to develop healthier snack alternatives suitable for gluten-sensitive and health-conscious consumers.

Sustainability spotlight

The present study highlights a sustainable approach to gluten-free food innovation by utilizing underutilized, nutrient-dense crops *viz.*, sprouted paheli dal flour (SPDF) and chayote tuber flour (CTF) as alternative ingredients in cracker production. By formulating crackers with these locally available and climate-resilient crops, the research supports biodiversity, promotes agricultural sustainability, and reduces reliance on refined wheat flour. The new product developed not only addresses dietary aspects but also improves nutritional quality by providing substantially higher levels of protein, fiber, and essential micronutrients. This work demonstrates how smart ingredient selection can promote the creation of healthier and more sustainable food systems.

1 Introduction

Chayote (*Sechium edule*), which belongs to the Cucurbitaceae family, grows mostly in eastern and western Himalayas. It grows as a backyard crop in the hilly terrain of most of the north-eastern states of India. Commonly known as squash, it is locally referred to as *Iskush* in Sikkim. Almost all parts of chayote *viz.*, fruits, roots or tubers, stems, and tender leaves are consumed. However, the consumption of chayote tubers by humans is very limited. Besides containing high levels of starch, the tubers are also low in gluten indicating that the chayote tubers could be a novel and high starch source. Fresh chayote tubers have high levels of phosphorus (34 mg/100 g, dry weight (DW)) and vitamin C content (19 mg/100 g, DW).[1] Although this tuber is

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normally consumed as a cooked vegetable in traditional cuisine, converting the tuber into a flour increases its value addition and its shelf life. The gluten free chayote tuber flour can act as a partial or full substitute for commonly used wheat or corn flour in baked products.[2]

Black gram (*Vigna mungo*) is the most significant crop among pulses and is grown in the lower altitude areas of Sikkim during the summer. Black gram in Sikkim is classified into two categories: large and black seeded and small and green seeded. The black gram varieties grown in Sikkim are Kalo dal, Paheli dal, T-9, Gwalior-2, Ujjain-4, and W.B.-17, with 'Paheli dal' being the most common due to its highest selling price. The sprouting of pulses has been identified as an economical and simple bioprocess that can enhance palatability, digestibility, and nutritional value by affecting the availability of nutrients, texture, sensory characteristics, antioxidants, and nutraceutical properties.[3] Germination is an efficient and inexpensive process to enhance the quality of legumes. During germination, several changes may occur in terms of nutrient quantity and type.[4] Germination of pulses also increases antioxidant activity which can be correlated with their phenolic content.[5] Both antioxidant activity and phenolic content vary with legume variety and germination conditions. A controlled sprouting process reduces the antinutritional factors in legumes.[6] Consumer awareness of health and nutrition has increased in recent years, leading to an increase in functional food consumption. Pulses contain significant amounts of phenolic compounds and dietary fiber; in particular, germinated pulses have great potential in the development of functional foods.[7]

In recent years, the global market for gluten-free products has expanded remarkably, driven by increasing consumer awareness of celiac disease, gluten intolerance, and the pursuit of healthier dietary alternatives. While numerous gluten-free formulations have been developed, many rely heavily on refined starches, gums, and synthetic hydrocolloids, which often compromise nutritional quality and sensory acceptability. Hence, there is growing scientific interest in the use of functional gluten-free ingredients derived from nutrient-dense, naturally gluten-free sources. Composite flour technology, which strategically blends flours from cereals, legumes, and tuber crops, has emerged as a promising approach to enhance both the nutritional and functional profiles of baked products.[8,9]

Crackers represent one of the most popular categories of baked snack products owing to their crisp texture, long shelf life, convenience, and wide consumer appeal. Traditionally made from refined wheat flour rich in starch and gluten, crackers are excellent candidates for reformulation using composite gluten-free flours to enhance their nutritional value and promote the inclusion of alternative plant-based ingredients. The chayote tuber, a locally underutilized tuber, offers high moisture retention, dietary fiber, and micronutrient density, while sprouted paheli dal provides high-quality plant proteins and bioactive compounds with enhanced digestibility and antioxidant activity. The integration of these flours may not only improve the nutritional quality and functional attributes of crackers but also promote value addition to indigenous crops with limited commercial utilization. Despite these promising characteristics, there is scant literature addressing their synergistic potential in developing gluten-free bakery products with desirable textural and sensory properties. Although earlier studies have investigated crackers, cookies *etc.*, from composite flours such as rice–cauliflower,[10] chayote–mung bean,[11] and wheat–oat–germinated barley,[12] gluten-free crackers formulated from chayote tubers and sprouted paheli dal (*Vigna mungo*) remain virtually unexplored.

Therefore, the present study seeks to address this research gap by formulating gluten-free composite flour crackers incorporating chayote tuber and sprouted paheli dal flour, and by systematically evaluating their nutritional composition, physicochemical characteristics, and consumer acceptability. The outcomes are expected to contribute novel insights into sustainable utilization of underexploited crops, advancing the development of nutritionally enriched, functional, and culturally relevant gluten-free snack alternatives.

2 Materials and methods

2.1 Materials

Chayote tuber, paheli dal, and other ingredients such as butter, sugar, salt, baking powder, refined oil, and refined wheat flour (WF) were all procured from the local markets of Ranipool, Sikkim, India. Chemicals used for analysis were procured from Loba Chemie Pvt. Ltd. and HiMedia. Packaging materials were procured from e-commerce platforms.

2.2 Preparation of chayote tuber flour and sprouted paheli dal flour

Procured chayote tubers were washed with potable water and peeled manually, rinsed and sliced into thin slices using a vegetable slicer (Generic, India). The sliced tubers were dried using a tray dryer (Techno Enterprise, India) at 60–65 °C until the moisture content dropped below 10% wet basis (w.b.). The dried tuber slices were then ground using a domestic flour mill (Natraj Aatamaker, India) followed by sieving through an 80-mesh sieve[13] to produce fine flour. For preparation of sprouted paheli dal, raw paheli dal was soaked in water for 12 h followed by germination for 20 h at 30 ± 2 °C and 80–85% relative humidity[14] in an incubator (ACMAS Technocracy, India). The fine flour of sprouted paheli dal was produced in the same way as chayote tuber flour. The prepared flours were packed in low-density polyethylene (LDPE) self-sealing pouches and stored till further analysis.

2.3 Preparation of composite flour

Chayote tuber flour and sprouted paheli dal flour were mixed at varying ratios to prepare various composite flour formulations. Simplex lattice mixture design using Design Expert 13.0 was used for preparation of twelve different composite flour formulations/blends. Refined Wheat Flour (RWF) was taken as control. The ratio of chayote tuber flour (CTF) to sprouted paheli dal flour (SPDF) varied from 50 : 50 to 70 : 30. To obtain homogeneous flour mixtures, flour was mixed manually. All flour samples were stored at room temperature (22 ± 2 °C) in air-tight containers until further analyses. The composite flour samples developed were analyzed for various physico-chemical and functional properties.

2.4 Preparation of composite flour crackers

In the present study, composite flour snack crackers were prepared from different flour blends of CTF and SPDF, and other ingredients *viz.*, jaggery powder, butter, water, baking powder, skim milk powder and salt using the method of Han *et al.*[15] All the ingredients were mixed continuously to form dough and the dough mixture was left to rest for 10 min at room temperature (22 ± 2 °C). The dough was then manually rolled into a thin sheet (2.5 mm thickness) and cut into shape (44 mm diameter) by using a dough cutter and placed onto a baking sheet/butter paper.[16] A forced-air convection oven (Usha Instruments and Chemicals, Kolkata, India) was used to bake the crackers for 10–15 min at 150 ± 3 °C.[17] Crackers prepared using refined wheat flour were produced as a control sample. The prepared crackers were analyzed for their quality in terms of various physico-chemical, color, textural, and sensory properties. Fig. 1 shows the process flowchart for production of CTF–SPDF crackers.

2.5 Analysis of composite flour blends

2.5.1 Physico-chemical analysis of flour blends. Proximate analysis of the components such as moisture, ash, fat, protein, carbohydrate and fiber content of different flour samples was carried out as per the standard protocol.[18] The moisture content was determined using an infrared moisture analyser (HC103, METTLER TOLEDO GERMANY) at 105 °C. The ash content was determined using a muffle furnace set at 550 °C for 5 h. The fat content was estimated using the Soxhlet extraction method in Soxhlet apparatus (SOCS PLUS, SCS 3). Protein content was determined using the Kjeldahl method. Crude fiber content was estimated using the method adopted by Padmore.[19] Carbohydrate content of flower was determined by the difference method (100 − (% moisture + % ash + % protein + % fat)). Ascorbic acid was determined by using 2,6-dichloroindophenol dye.[20] 10 g of the sample was mixed with 3% metaphosphoric acid (HPO_3) solution. A final volume of 100 mL was prepared using HPO_3, followed by filtration and centrifugation at 8500 rpm for 10 min. An aliquot of 10 mL of HPO_3 extract was titrated with the standard dye to the pink end point for 15 s. Ascorbic acid content was expressed in mg/100 g sample. All the analyses were performed in triplicate.

2.5.2 Total phenolic content of flour blends. Total phenolic content (TPC) was determined using the Folin–Ciocalteau method described by Mamilla and Mishra.[21] A standard curve was plotted using gallic acid as standard. About 10 mg of flour sample was dissolved in 6 mL of methanol and shaken in an incubator for 3 h at room temperature. The mixture was then filtered to obtain a clear extract using Whatman No. 1 filter paper. The homogenized mixture was centrifuged at 4000 rpm for 15 min and the supernatant was collected in vials. 100 μL of extract were mixed with 500 μL of Folin–Ciocalteu solution

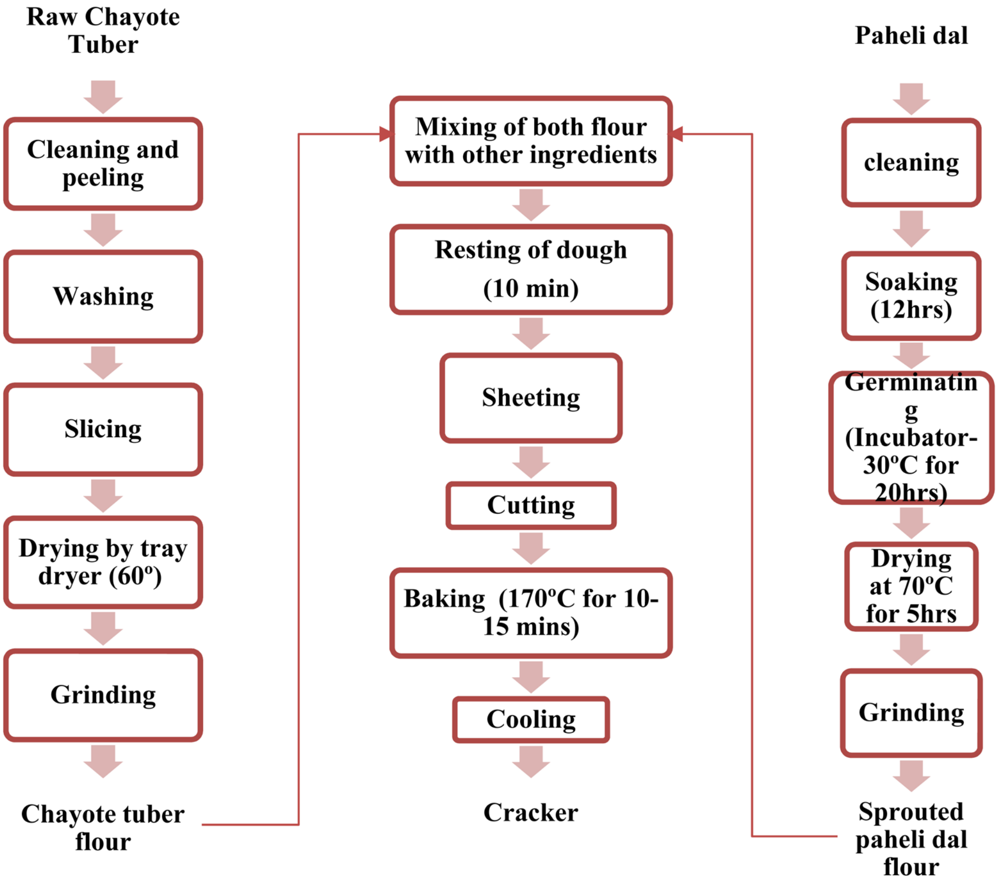

Fig. 1 Process flowchart for production of chayote tuber-sprouted paheli dal crackers.

(previously diluted 1 : 1 with distilled water) and allowed to stand at room temperature for 5 min followed by addition of 500 µL of sodium bicarbonate solution (20% w/v). The blue mixture thus obtained was kept in a dark incubator at room temperature for 30 min. The absorbance was measured at 760 nm in a UV-VIS spectrophotometer (UV-2600, Shimadzu, Japan). Total phenolic concentrations were expressed as mg gallic acid equivalent (GAE)/100 g dry weight. All the analyses were performed in triplicate.

2.5.3 Color analysis. The color of flour samples was measured using a Chroma Meter (CR-410, Konica Minolta, Japan). The display was set to the CIELAB scale, with L^*, a^*, and b^* coordinates, where L^* represents the color's brightness and varies between 0 (dark) and 100 (light), a^* varies from green (−ve) to red (+ve), and b^* varies from blue (−ve) to yellow (+ve). To determine the color profile of food elements, saturation index or chroma (C^*) and hue angle (h^*) were also measured. Angles of 0° or 360° represent red hue, whereas angles of 90°, 180°, and 270° on the other hand symbolize the hues of yellow, green, and blue, respectively. All the analyses were performed in triplicate. Eqn (1) and (2) were used to determine the chroma (C^*) and hue angle (h^*), respectively.[22]

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{1}$$

where C^* = chroma; a^* = green (−ve) and red (+ve); b^* = blue (−ve) and yellow (+ve).

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{2}$$

where h^* = hue angle; a^* = green (−ve) and red (+ve); b^* = blue (−ve) and yellow (+ve).

2.5.4 Gluten content of flour samples. Gluten extraction from different flours was performed according to AACC.[23] Dough was prepared using 2% NaCl solution and 60% weight of flour sample. The prepared dough was dipped in water for 40 min. The dough was continuously washed with water till all the traces of starch were removed and the water became clear. The remaining portion of the dough was weighed. The dough weight of the wet gluten was taken to estimate the gluten yield. All the analyses were performed in triplicate.

2.5.5 Bulk density of the flour samples. `The bulk density of all flour samples was determined by using the gravimetric method described by Baljeet *et al.*[24] 50 g of weighed sample was poured into a 100 mL measuring cylinder. The bottom of the cylinder was tapped repeatedly on a fixed slab to maintain a constant volume. Based on the mass/volume ratio of the sample, bulk density (BD) was calculated. All the analyses were performed in triplicate.

2.5.6 Characteristics of functional properties of composite flour blends. The functional properties of composite flours are important in production of new products. Functional properties such as water absorption capacity (WAC), oil absorption capacity (OAC), foam capacity (FC), and foam stability (FS) of all flour samples were determined as follows.

2.5.6.1 Water and oil absorption capacity. Water absorption capacity and oil absorption capacity of flour samples were determined using the method described by Sultan *et al.*[25] The flour sample was mixed with 10 mL of distilled water and 10 mL of mustard oil to determine the absorption capacity of water and oil. It was then kept at room temperature for 30 min and centrifuged for 10 min at 2000 rpm in a centrifuge (3K30, Sigma, Germany). After centrifugation, the supernatant was decanted and allowed to drain for 5 min on paper towels. The residual WAC/OAC was calculated by weighing the sample and expressed as a percentage of water or oil absorbed per gram. Eqn (3) was used for calculating WAC/OAC. All the analyses were performed in triplicate.

$$\text{WAC/OAC} = \frac{\text{weight of residue} - \text{weight of sample}}{\text{weight of sample}} \times 100 \tag{3}$$

2.5.6.2 Foaming capacity (FC) and foam stability (FS). Foaming capacity and foam stability were measured according to the procedure reported by Wani *et al.*[26] 2 g of flour samples were mixed with 50 mL of distilled water in a 100 mL measuring cylinder. The suspension was mixed thoroughly for foam formation. After blending, the mixture was transferred to a graduated cylinder and kept undisturbed for 30 s. The volume of foam was then recorded. Foaming capacity was calculated by using eqn (4).

$$\text{FC (\%)} = \frac{(\text{volume after whipping} - \text{volume before whipping}) \times 100}{\text{volume before whipping}} \tag{4}$$

Foam volume was recorded 1 h after foaming to determine foam stability as a percentage of the original foam volume using eqn (5). All the analyses were performed in triplicate.

$$\text{FS (\%)} = \frac{\text{foam volume after standing time}}{\text{initial foam volume}} \times 100 \tag{5}$$

2.6 Physico-chemical characteristics of composite flour crackers

Physical and chemical properties of the developed composite flour crackers were analyzed to determine their quality. The physico-chemical properties analyzed included spread ratio, hardness, color, moisture content, protein content, ash content, fat content, crude fiber content, carbohydrate content, ascorbic acid content, total phenolic content, and antioxidant activity. All the analyses were performed in triplicate.

2.6.1 Proximate composition of crackers. The proximate composition of crackers was determined as per the method described in Section 2.5.1.

2.6.2 Ascorbic acid content and total phenolic content. Ascorbic acid content and TPC of crackers were determined according to Sections 2.5.1 and 2.5.2. For TPC and ascorbic acid content, an extract of the developed crackers was prepared. The cracker samples were ground and mixed with 80% methanol in a ratio of 1 : 10. Then the mixture was mixed in a magnetic stirrer for 1 h. Then, the mixed sample was centrifuged in a centrifuge at 4500 rpm for 10 min. The supernatant was collected and used for the analysis.

2.6.3 Antioxidant activity. The antioxidant activity (AA) of crackers was determined by the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging method with some modifications.[27] Radical scavenging activity assay/DPPH extraction was carried out by thoroughly shaking 2 g of cracker sample in 10 mL of 80% methanol for 24 h at room temperature. The mixture was then filtered to remove debris from the extract-containing methanol using grade 1 Whatman filter paper. 3.9 mL of DPPH solution was added to 0.1 mL of methanol extract solution. They were thoroughly mixed and incubated in the dark for 30 min. The absorbance was measured at 517 nm using a UV spectrophotometer. The control was prepared with the methanolic dilution of DPPH. Lower absorbance of the reaction mixture indicates higher free radical scavenging activity. The antioxidant activity/DPPF radial scavenging activity was measured using eqn (6).

$$\text{DPPH radical scavenging activity } (\%) = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100 \tag{6}$$

where A_{control} = absorbance of control; A_{sample} = absorbance of sample.

2.6.4 Spread ratio. The quality of crackers is commonly determined by the spread ratio which is a relatively complex phenomenon influenced by a wide variety of factors.[28] The spread ratio was determined by the method followed by Zoulias *et al.*[29] as the relationship between cracker diameter and thickness. A digital Vernier caliper (Baker Gauges India Private Limited) was used to measure their dimensions.

2.6.5 Hardness and color. Texture is amongst the very important characteristics that make a significant contribution to the overall acceptance of food products. The hardness/snap force of the baked crackers was analyzed by the procedure followed by Singh and Singh[30] using a texture analyzer (TA-XT2i, Stable Micro Systems, UK) in compression mode with a sharp cutting blade. Pre-test, test, and post-test speeds were 1.5, 2, and 10 mm s^{-1}, respectively. In order to measure hardness, peak force was estimated from the force–time plots obtained from the software. Three crackers per treatment were analyzed and average values were calculated. The color of the crackers was analysed as per the method described in Section 2.5.3.

2.6.6 Acidity of the extracted fat. The acid insoluble ash content and acidity of the extracted fat of the crackers were determined by the method described in IS (1011:2002).[31] About 10 g of ground cracker sample was weighed and transferred to a thimble and plugged from the top with cotton and filter paper. The fat was extracted with petroleum ether using Soxhlet apparatus for 1 to 2 h and the solvent was evaporated off in the flask on a water-bath. The traces of the residual solvent from the flask were removed by placing it in a hot air oven for 30 min. The flask was cooled and the extracted fat was removed in a tared 250 mL flat-bottomed flask to which 50 mL of ethanol was added. 1 mL of phenolphthalein reagent was added to the flask and titrated against potassium hydroxide (KOH) solution to a distinct pink color.

2.6.7 Acid insoluble ash. The acid insoluble ash content of the crackers was determined by the method described in IS (1011:2002).[31] About 10 g of ground cracker sample was weighed accurately in a silica dish and kept in a muffle furnace at 550 ± 5 °C until ash was obtained. The silica dish was then cooled to room temperature and to it 25 mL of HCl was added. Then, the dish was covered with a watch-glass and heated in a water-bath for 10 min. The samples on the dish were then mixed followed by filtration using Whatman filter paper No. 42. The filter paper was washed with water till it was free from acid as indicated by blue litmus paper. The washed filter paper was placed in a silica dish and ashing was again done in a muffle furnace as stated before. The dish was cooled in a desiccator and weighed.

2.6.8 Sensory analysis of crackers. The sensory evaluation of the crackers was carried out by 30 semi-trained panelists in the 20 to 60 years age group. The samples were coded, labelled, and presented randomly along with sensory evaluation sheets to the panelists for sensory evaluation. Ratings were given on the different sensory attributes like appearance/color, flavour/taste, aroma, mouth feel, texture/crispiness and overall acceptability. A nine-point hedonic scale was employed as: 1 = dislike extremely; 2 = dislike very much; 3 = dislike moderately; 4 = dislike slightly; 5 = neither like nor dislike; 6 = like slightly; 7 = like moderately; 8 = like very much; 9 = like extremely for scoring.[32,33] The sensory index was calculated as a percentage with the help of the total sensory score and the total sensory scale. The sensory index was calculated using eqn (7).

$$\text{Sensory index} = \frac{\text{total sensory score}}{\text{total sensory scale}} \times 100 \tag{7}$$

2.7 Statistical analysis and optimization of the composite flour cracker formulation

Statistical analysis was done through ANOVA (analysis of variance), and a Duncan Multiple Range Test (DMRT) using SPSS 26.0/Design Expert software. Numerical optimization with the desirability function was used to optimize the composite flour formulation using Design Expert software (version 13.0) to achieve the best cracker formulation. Models were developed for responses *viz.*, moisture content, acid insoluble ash, acidity of the extracted fat, hardness, overall acceptability and spread ratio to determine the effect of formulations and predict the responses. The optimization criteria were: maximum hardness, maximum overall acceptability[34] and maximum spread ratio.[35] The appropriate solution with the highest combined desirability value was chosen as the optimum formulation for composite flour crackers. The predicted responses at the optimized formulation were validated by preparing crackers using the optimized formulation.

3 Results and discussion

3.1 Physico-chemical properties of composite flour blends

The moisture content of all composite flour samples decreased significantly ($p < 0.05$) from 9.09% to 8.22% wet basis (w.b.) with the decrease in CTF content (Table 1). The control refined wheat

Table 1 Physico-chemical properties of composite flour blends[a]

Samples	MC (% w.b.)	Protein (%)	Ash (%)	Fat (%)	Fiber (%)	Carbohydrates (%)	Ascorbic acid (mg/100 g)	Total phenolic content (mg GAE/100 g)
S1	$9.08^{e} \pm 0.11$	$12.78^{a} \pm 0.4$	$3.87^{e} \pm 0.15$	$1.98^{a} \pm 0.12$	$2.44^{a} \pm 0.01$	$72.29^{c} \pm 0.3$	19.00 ± 0.6	333.10 ± 0.8
S2	$9.09^{e} \pm 0.05$	$13.02^{a} \pm 0.5$	$3.80^{e} \pm 0.02$	$1.92^{a} \pm 0.06$	$2.43^{a} \pm 0.01$	$72.17^{bc} \pm 0.5$	18.00 ± 0.6	332.92 ± 0.0
S3	$9.08^{e} \pm 0.05$	$12.96^{a} \pm 0.7$	$3.87^{e} \pm 0.01$	$1.76^{a} \pm 0.61$	$2.39^{a} \pm 0.02$	$72.33^{bc} \pm 0.7$	19.00 ± 0.6	332.57 ± 0.3
S4	$9.09^{e} \pm 0.15$	$12.58^{a} \pm 0.3$	$3.81^{e} \pm 0.11$	$1.56^{a} \pm 0.01$	$2.45^{a} \pm 0.01$	$72.96^{c} \pm 0.3$	19.00 ± 0.6	332.39 ± 0.5
S5	$8.87^{d} \pm 0.05$	$13.92^{b} \pm 0.3$	$3.75^{d} \pm 0.06$	$1.69^{b} \pm 0.01$	$2.59^{b} \pm 0.02$	$72.77^{bc} \pm 0.3$	19.50 ± 0.5	340.60 ± 0.7
S6	$8.52^{c} \pm 0.03$	$15.02^{c} \pm 0.3$	$3.72^{bc} \pm 0.10$	$2.02^{c} \pm 0.01$	$2.64^{c} \pm 0.02$	$70.72^{bc} \pm 0.3$	20.00 ± 0.6	348.18 ± 0.6
S7	$8.58^{c} \pm 0.17$	$14.87^{c} \pm 0.5$	$3.67^{b} \pm 0.06$	$2.16^{c} \pm 0.02$	$2.65^{c} \pm 0.01$	$70.72^{bc} \pm 0.5$	20.00 ± 0.6	348.01 ± 0.8
S8	$8.55^{c} \pm 0.05$	$15.02^{c} \pm 0.5$	$3.68^{cd} \pm 0.00$	$1.99^{c} \pm 0.04$	$2.66^{c} \pm 0.01$	$70.76^{bc} \pm 0.5$	20.00 ± 1.0	347.92 ± 1.2
S9	$8.95^{b} \pm 0.06$	$15.89^{d} \pm 0.1$	$3.69^{a} \pm 0.06$	$2.13^{d} \pm 0.01$	$2.70^{d} \pm 0.02$	$79.34^{ab} \pm 0.2$	20.50 ± 0.5	356.65 ± 0.9
S10	$8.35^{a} \pm 0.05$	$16.35^{e} \pm 0.7$	$3.65^{ab} \pm 0.06$	$2.19^{e} \pm 0.05$	$2.75^{e} \pm 0.03$	$69.46^{ab} \pm 0.7$	21.00 ± 0.6	362.04 ± 0.5
S11	$8.26^{a} \pm 0.23$	$16.35^{e} \pm 0.3$	$3.62^{ab} \pm 0.00$	$2.16^{e} \pm 0.01$	$2.78^{e} \pm 0.01$	$69.61^{ab} \pm 0.3$	21.00 ± 0.6	366.28 ± 1.4
S12	$8.22^{a} \pm 0.37$	$16.49^{e} \pm 0.2$	$3.58^{ab} \pm 0.06$	$2.15^{e} \pm 0.01$	$2.75^{e} \pm 0.01$	$69.56^{a} \pm 0.2$	21.00 ± 0.6	362.57 ± 0.3
Control	$13.22^{f} \pm 0.21$	$12.46^{a} \pm 0.2$	$0.97^{a} \pm 0.23$	$1.75^{e} \pm 0.03$	$0.65^{f} \pm 0.05$	$72.70^{c} \pm 0.02$	5.02 ± 0.3	303.90 ± 0.02

[a] Values are means ± SD of triplicates. Different superscripts in the same column indicate a significant difference at the 95% confidence level; MC: moisture content, control: refined wheat flour.

flour contained moisture content of 13.22% w.b. which was higher than that of all composite flour formulations. The SPDF incorporation in composite flour showed a significant ($p < 0.05$) decrease in moisture content by 36.86%. Lower moisture content in SPDF (8.71% w.b.) may be the reason for the decreased moisture content of composite flour, aligning with observations by Tharise *et al.*[13] for the composite flour prepared from cassava, rice, potato, soybean and xanthan gum.

Composite flour with high SPDF substitution had significantly higher ($p < 0.05$) protein and fat contents. Specifically, the content of protein increased by 23.72% and that of fat by 30.5% with an increase in SPDF level from 30% to 50% which may be possibly due to the higher content of protein (24.74%) and fat (2.3%) in SPDF. The control refined wheat flour contained 12.46% protein which was lower than that of all composite flour formulations. This result agrees with those reported by Atudorei *et al.*,[36] for germinated bean flour–wheat composite flour and also reported 1.12% of fat content in wheat flour and 1.4% fat in germinated green bean flour. Tharise *et al.*[13] reported 1.33 to 4.19% fat content in the composite flour prepared from cassava, rice, potato, soybean and xanthan gum. The observed increase in fat content was found to be consistent with findings of Bazaz *et al.*[37] where the fat content increased with increased proportion of sprouted green gram flour to potato flour. The CTF–SPDF composite flour was found to contain 11.62–46.31% more protein and about 22.85% higher fat than refined wheat flour.

The ash content of all composite flour samples significantly decreased ($p < 0.05$) from 3.87% to 3.58% (dry basis) with the decrease in CTF content from 70% to 50% and increase in SPDF content from 30% to 50% (Table 1). A decrease by 7.49% in ash content was observed with an increase in SPDF content in composite flour. This could be attributed to the relatively lower ash content in SPDF (3.37%), aligning with the results of Bazaz *et al.*,[37] who noted a similar decrease in ash content with reduced potato flour in composite flour developed from sprouted green gram flour and potato flour. Compared to refined wheat flour, CTF and SPDF composite flour provided about 270% more ash indicating nutrient richness of the new composite flour. A significant ($p < 0.05$) increase in fiber content (2.39–2.78%) was observed in composite flour containing higher SPDF, which can be attributed to higher fiber concentration in SPDF (5.05%) relative to CTF. As reported by Tharise *et al.*,[13] the vegetable-bean based composite flour prepared from cassava, rice, potato, soybean, and xanthan gum contained 1.13–1.94% fiber which is close to the fiber content obtained in the present study. Compared to refined wheat flour, CTF and SPDF composite flour showed about 323% more fiber.

Carbohydrate content in all composite flour samples was found to be in the range of 69.46–79.34% (Table 1) which was similar to refined wheat flour samples (72.7%). The increase in carbohydrate content with an increase in chayote tuber flour content is attributed to higher carbohydrate content of CTF (72.76%) as compared to SPDF. This finding corroborates those reported by Benayad *et al.*[38] for fortified faba bean flour. Gluten was not detected in all composite flour samples that were prepared from CTF and SPDF. The gluten content of the control sample (refined WF) was 36.05%, which was in line with the findings published by Kaushik *et al.*[39]

3.2 Ascorbic acid and total phenolic content of flour

The values of ascorbic acid and total phenolic content are listed in Table 1. A significant increase in ascorbic acid (18.00 to 21.00 mg/100 g) and total phenolic content (332.39 to 366.28 mg gallic acid equivalent (GAE)/100 g) was observed in all composite flour samples with the increase in SPDF content from 30% to 50%, which may be due to higher ascorbic acid (23.80 mg/100 g) and total phenolic content (398.00 mg GAE/100 g) in SPDF. Sprouting results in an increase in the TPC content of the SPDF due to phenolic biosynthesis and release of cell wall-bound phenolics during sprouting.[40] Germination alters the phenolic content due to the change of enzyme activity, mineral content, and vitamins.[41] Shiga *et al.*[1] reported 19 mg/100 g ascorbic acid in the fresh tuberized roots of *S. edule* whereas Masood *et al.*[42] reported about 20.78 mg/100 g ascorbic acid content in sprouted moong bean. These results are consistent with the findings of the present study. The control refined wheat flour contained 5.02 mg/100 g ascorbic acid and 303.90 mg GAE/100 g total phenolic content which was 9.5–20.52% lower than those of all composite flour formulations developed.

3.3 Color analysis of flour

Based on the color parameter data, hue angle and chroma were calculated to express qualitative and quantitative measurements of color. The color parameters *viz.*, L^* (lightness), a^* (redness) and b^* (yellowness) values were in the range of 89.65 to 95.99, −1.13 to −0.70 and 11.70 to 13.61, respectively. The lightness values of composite flour samples were close to 100 indicating high brightness of the composite flour samples. The low and negative a^* values suggest a neutral to slightly red color of composite flour samples. The positive b^* values indicating yellowness were also found to be lower which gives the composite flour a light yellow color. The lightness and yellowness values of composite flour blends increased significantly ($p < 0.05$) with the increase in CTF whereas the redness of the composite flour samples increased significantly ($p < 0.05$) with an increase in SPDF and decrease in CTF (Table 2). Refined wheat flour showed an L^* (lightness) value of 67.45, a^* (redness) value of 0.22, and b^* (yellowness) value of 8.83 which were lower than those observed for composite flour formulations. This aligns with earlier work by Tharise *et al.*,[13] for the composite flour prepared from cassava, rice, potato, soybean and xanthan gum. Hue angle and chroma were in the range of 93.48 to 94.75° and 11.56 to 13.66, respectively, for the developed CTF–SPDF composite flour blends. Refined wheat flour had 94.07° and 6.17 hue angle and chroma, respectively. The chroma value, which indicates color saturation, was found to be significantly lower for control refined wheat flour as compared to CTF–SPDF composite flour blends.[16]

3.4 Bulk density of flour

The bulk density of all composite flour samples decreased significantly ($p < 0.05$) from 730.00 to 772.66 kg m^{-3} with the decrease in CTF content (Table 2). The bulk density of control refined wheat flour was about 733.00 kg m^{-3}, which was similar to that of the composite flour formulations. Higher SPDF incorporation resulted in a significant ($p < 0.05$) drop in bulk density (5.45%), most likely owing to its lower bulk density in comparison to CTF (840.00 kg m^{-3}). Comparable decreases in bulk density as a result of ingredient replacement have been reported in blends using Bambara groundnut and protein isolate[43] and composite flours made of cassava, corn, and soybean.[44]

3.5 Functional properties

The water absorption capacity of all composite flour samples increased significantly ($p < 0.05$) from 86.34 to 110.00% with the increase in SPDF content (Table 3) in the flour samples. The control refined wheat flour showed a WAC of 94.53% which was found to be higher than that of all composite flour formulations. The SPDF incorporation in composite flour showed a significant ($p < 0.05$) increase in water absorption by 21.5% aligning with the observations of Chandra *et al.*,[45] where WAC increased with an increase in green gram flour content in composite flours. The reason for this increase may be attributed to the higher water absorption capacity of SPDF (184.00%) as compared to the water absorption capacity of CTF. These differences in water absorption capacity may be due to differences in protein concentration and water interaction as suggested by Butt and Rizwana.[46] Protein present in SPDF has both hydrophilic and hydrophobic nature because of which it can interact with water in foods leading to higher WAC.[47] As observed in this study, flours with high WAC are potentially useful for bakery products, as they prevent staling while reducing moisture loss.[45,48] Hence, composite flours developed in the present study that had higher WAC could be suitable alternatives to refined wheat flour for production of bakery products.

Oil absorption capacity of all composite flour samples ranged from 97.33–144.67%. The OAC of composite flours containing varying proportions of CTF and SPDF differed significantly ($p < 0.001$) across formulations. A gradual increase in OAC was observed with decreasing levels of chayote tuber flour and a corresponding increase in SPDF, indicating a strong dependence of oil-binding ability on the protein and fiber rich

Table 2 Physical properties of composite flour blends[a]

Samples	Bulk density (kg m^{-3})	L^*	a^*	b^*	Chroma	Hue angle (°)
S1	$772.66^{e} \pm 4.5$	$93.58^{f} \pm 0.55$	$-0.90^{b} \pm 0.01$	$12.62^{e} \pm 0.05$	$12.65^{b} \pm 0.05$	$94.07^{a} \pm 0.07$
S2	$762.00^{d} \pm 4.6$	$93.60^{f} \pm 0.01$	$-1.13^{a} \pm 0.05$	$13.61^{f} \pm 0.05$	$13.66^{b} \pm 0.05$	$94.75^{a} \pm 0.02$
S3	$762.33^{d} \pm 1.2$	$93.90^{g} \pm 0.03$	$-0.88^{bc} \pm 0.05$	$12.60^{e} \pm 0.01$	$12.63^{b} \pm 0.09$	$94.01^{a} \pm 0.02$
S4	$762.33^{d} \pm 1.5$	$95.99^{h} \pm 0.01$	$-0.86^{d} \pm 0.01$	$13.21^{g} \pm 0.05$	$13.24^{b} \pm 0.05$	$93.72^{a} \pm 0.01$
S5	$756.33^{d} \pm 2.1$	$93.43^{f} \pm 0.11$	$-0.86^{d} \pm 0.01$	$12.61^{e} \pm 0.01$	$12.63^{b} \pm 0.01$	$93.90^{a} \pm 0.01$
S6	$748.00^{c} \pm 3.0$	$92.44^{e} \pm 0.01$	$-0.85^{de} \pm 0.01$	$12.44^{de} \pm 0.01$	$12.46^{b} \pm 0.04$	$93.93^{a} \pm 0.02$
S7	$749.00^{c} \pm 1.0$	$92.40^{e} \pm 0.03$	$-0.87^{cd} \pm 0.01$	$12.46^{de} \pm 0.01$	$12.49^{b} \pm 0.07$	$93.99^{a} \pm 0.04$
S8	$749.00^{c} \pm 1.0$	$92.46^{e} \pm 0.21$	$-0.87^{cd} \pm 0.02$	$12.37^{d} \pm 0.32$	$12.55^{b} \pm 0.05$	$93.98^{a} \pm 0.10$
S9	$738.00^{b} \pm 10.4$	$91.28^{d} \pm 0.01$	$-0.84^{e} \pm 0.02$	$12.04^{c} \pm 0.06$	$12.06^{b} \pm 0.06$	$93.99^{a} \pm 0.02$
S10	$730.00^{a} \pm 2.5$	$90.77^{c} \pm 0.02$	$-0.75^{f} \pm 0.01$	$11.76^{b} \pm 0.01$	$11.78^{b} \pm 0.06$	$93.64^{a} \pm 0.04$
S11	$735.00^{ab} \pm 2.6$	$89.65^{b} \pm 0.01$	$-0.72^{g} \pm 0.01$	$11.73^{b} \pm 0.01$	$11.75^{b} \pm 0.01$	$93.54^{a} \pm 0.05$
S12	$734.40^{ab} \pm 2.1$	$89.65^{b} \pm 0.01$	$-0.70^{h} \pm 0.01$	$11.70^{b} \pm 0.25$	$11.56^{b} \pm 0.02$	$93.48^{a} \pm 0.05$
Control	$733.00^{ab} \pm 1.0$	$67.45^{a} \pm 0.10$	$0.22^{i} \pm 0.01$	$8.83^{a} \pm 0.01$	$6.17^{a} \pm 4.6$	$94.07^{a} \pm 0.07$

[a] Values are means ± SD of triplicates. Different superscripts in the same column indicate a significant difference at the 95% confidence level.

Table 3 Functional properties of composition of composite flour blends[a]

Samples	WAC (%)	OAC (%)	FC (%)	FS (%)
S1	$86.34^{a} \pm 0.03$	$97.33^{a} \pm 0.03$	$82.05^{b} \pm 0.03$	$97.88^{b} \pm 0.03$
S2	$89.00^{a} \pm 0.02$	$98.67^{b} \pm 0.03$	$91.02^{c} \pm 0.03$	$97.98^{c} \pm 0.03$
S3	$87.67^{a} \pm 0.03$	$103.67^{c} \pm 0.03$	$83.97^{b} \pm 0.03$	$97.91^{b} \pm 0.03$
S4	$87.34^{a} \pm 0.02$	$107.00^{d} \pm 0.03$	$89.74^{c} \pm 0.03$	$97.97^{c} \pm 0.03$
S5	$90.34^{a} \pm 0.03$	$119.67^{e} \pm 0.03$	$106.41^{d} \pm 0.03$	$98.13^{d} \pm 0.03$
S6	$95.00^{bc} \pm 0.04$	$133.00^{f} \pm 0.03$	$120.51^{ef} \pm 0.03$	$98.26^{ef} \pm 0.03$
S7	$99.00^{cd} \pm 0.02$	$134.67^{g} \pm 0.03$	$124.35^{f} \pm 0.03$	$98.29^{f} \pm 0.03$
S8	$97.00^{bc} \pm 0.03$	$134.33^{h} \pm 0.03$	$117.94^{de} \pm 0.03$	$98.23^{e} \pm 0.03$
S9	$102.67^{d} \pm 0.02$	$139.00^{i} \pm 0.03$	$130.77^{fg} \pm 0.03$	$98.33^{g} \pm 0.03$
S10	$108.34^{e} \pm 0.03$	$143.67^{j} \pm 0.03$	$141.02^{h} \pm 0.03$	$98.40^{h} \pm 0.03$
S11	$109.67^{e} \pm 0.02$	$144.33^{k} \pm 0.03$	$142.31^{h} \pm 0.03$	$98.41^{h} \pm 0.03$
S12	$110.00^{e} \pm 0.03$	$144.00^{l} \pm 0.03$	$146.26^{h} \pm 0.03$	$98.44^{h} \pm 0.03$
Control	$94.53^{b} \pm 0.01$	$146.00^{m} \pm 0.03$	$10.80^{a} \pm 0.03$	$88.75^{a} \pm 0.03$

[a] Values are means ± SD of triplicates. Different superscripts in the same column indicate a significant difference at the 95% confidence level; WAC: water absorption capacity, OAC: oil absorption capacity, FC: foam capacity, FS: foam stability.

legume component. The lowest OAC was recorded for the 70 : 30 ratio, while the highest was observed in the 50 : 50 blend. *Post hoc* (Tukey's HSD) analysis revealed that the OAC of higher SPDF formulations (≥40%) differed significantly ($p < 0.01$) from that of the lower SPDF ratio (70 : 30), while no significant variation ($p > 0.05$) was found among the 60 : 40, 55 : 45, and 50 : 50 combinations, suggesting a plateau effect at higher SPDF levels. The most important chemical component that acts on OAC is protein as present in SPDF that consists of both hydrophilic and hydrophobic parts.[48] Refined wheat flour showed OAC of 146.67% which was slightly higher than composite flour. The higher fat content in CTF and SPDF as compared to refined wheat flour might have adversely affected the OAC of the composite flours.[45] The observations of OAC from this present study aligns well with those of Ugwuona *et al.*,[44] for composite flour of cassava, corn and soyabean flour and Kaushal *et al.*,[49] for the composite flour of taro (*Colocasia esculenta*), rice (*Oryza sativa*), pigeon pea (*Cajanus cajan*) flour.

Foaming capacity (FC) describes the amount of interfacial space created by the protein.[50] Foaming capacity of all composite flour samples of the ranged from 82.05 to 146.26% which is significantly higher (86–92%) than refined wheat flour (10.80%). The presence of protein in SPDF led to higher foaming capacity in all composite flour blends. This is consistent with the findings of Chandra *et al.*,[45] who reported the increase in FC with increase in green gram flour content for rice–potato–green gram–wheat composite flour.

Foam stability of all composite flour samples varied in the range of 97.88 to 98.44% as shown in Table 3. Refined wheat flour showed FS of 88.5% which was 9.58–10.1% lower than CTF–SPDF composite flour. Significant ($p < 0.05$) increase in FS with increase in SPDF content in composite flour was observed. The presence of higher protein concentrations in SPDF might have increased the foam stability by promoting protein–protein interactions near the air water interface which resulted in a multilayer film that offers high viscoelastic resistance to bubble coalescence.[51] A comparable increase in foam stability was also observed in the study by Chandra *et al.*,[45] which was due to the increase in green gram flour content in composite flour.

3.6 Proximate analysis of crackers

The values of proximate analysis are listed in Table 4. The moisture content of all composite flour crackers decreased significantly ($p < 0.05$) from 4.22 to 3.08% w.b. with decrease in CTF content. The control refined wheat flour contained moisture content of 3.33% w.b. which was slightly higher than all composite flour formulations. The increased SPDF incorporation in composite flour showed significant ($p < 0.05$) decrease in moisture content by 27.01%, the reason being lower moisture content in SPDF 8.71% w.b. The moisture contents of the developed crackers were well within 5% (the upper limit) as prescribed in IS1011-2002, which aligns well with those of Roger *et al.*,[52] who found similar trend in the biscuits made from wheat–sweet potato–soyabean composite flour. Composite flour crackers showed higher protein contents (12.68–18.38%) than refined wheat flour crackers (9.99%). With increased level of SPDF substitution, significantly ($p < 0.05$) higher (31.02%) protein content was observed in composite flour crackers. These results agree with those reported by Millar *et al.*,[16] Roger *et al.*,[52] and Venkatachalam and Nagarajan[53] all of whom found improvements in protein content with increased legume flour substitution.

The fat content of composite flour crackers increased significantly ($p < 0.05$) by 29.54% with an increase in the SPDF level from 30% to 50%, possibly due to the higher fat content of SPDF. The control refined wheat flour crackers contained 9.45% fat which was lower than all composite flour crackers. A similar trend of increase in fat content with increased proportion of sprouted green gram flour to potato flour was observed by Bazaz *et al.*,[37] for weaning food prepared from sprouted green gram flour and potato flour. The ash content of all composite flour samples decreased significantly ($p < 0.05$) from 3.28 to 2.03 (dry basis) with the decrease in CTF content from 70% to 50% and increase in SPDF content from 30% to 50%. A decrease by 38% in ash content was observed with an increase in SPDF content in composite flour, consistent with the findings of Bazaz *et al.*,[37] who observed a decrease in ash content in weaning food prepared from sprouted green gram flour and potato flour with

Table 4 Proximate composition of crackers[a]

Samples	MC (%)	Ash (%)	Protein (%)	Fat (%)	Fiber (%)	Carbohydrate (%)
S1	$4.22^{h} \pm 0.01$	$3.15^{i} \pm 0.02$	$12.68^{a} \pm 0.01$	$9.58^{b} \pm 0.01$	$1.55^{a} \pm 0.02$	$70.37^{k} \pm 0.02$
S2	$4.12^{g} \pm 0.01$	$3.28^{j} \pm 0.02$	$13.13^{d} \pm 0.01$	$9.55^{a} \pm 0.02$	$1.55^{a} \pm 0.01$	$69.93^{h} \pm 0.01$
S3	$4.21^{h} \pm 0.01$	$3.28^{j} \pm 0.01$	$12.87^{b} \pm 0.01$	$9.54^{a} \pm 0.01$	$1.56^{a} \pm 0.01$	$70.10^{i} \pm 0.02$
S4	$4.11^{g} \pm 0.01$	$3.12^{h} \pm 0.01$	$12.92^{c} \pm 0.03$	$9.59^{b} \pm 0.02$	$1.56^{a} \pm 0.01$	$70.26^{j} \pm 0.01$
S5	$3.88^{f} \pm 0.01$	$3.05^{g} \pm 0.02$	$13.78^{e} \pm 0.02$	$10.54^{c} \pm 0.04$	2.05b ± 0.06	$68.75^{g} \pm 0.05$
S6	$3.71^{e} \pm 0.01$	$2.55^{d} \pm 0.02$	$15.53^{g} \pm 0.03$	$11.50^{d} \pm 0.03$	$2.47^{d} \pm 0.01$	$66.71^{d} \pm 0.02$
S7	$3.65^{d} \pm 0.01$	$2.67^{e} \pm 0.01$	$15.31^{f} \pm 0.01$	$11.53^{e} \pm 0.03$	$2.40^{c} \pm 0.05$	$66.83^{f} \pm 0.07$
S8	$3.69^{e} \pm 0.03$	$2.76^{f} \pm 0.01$	$15.31^{f} \pm 0.02$	$11.50^{d} \pm 0.01$	$2.39^{c} \pm 0.04$	$6674^{e} \pm 0.06$
S9	$3.32^{c} \pm 0.01$	$2.39^{c} \pm 0.01$	$16.63^{h} \pm 0.01$	$12.47^{f} \pm 0.02$	$2.83^{e} \pm 0.01$	$65.20^{e} \pm 0.04$
S10	$3.08^{a} \pm 0.01$	$2.05^{ab} \pm 0.00$	$18.38^{j} \pm 0.03$	$13.54^{gh} \pm 0.03$	$3.19^{f} \pm 0.06$	$62.95^{a} \pm 0.06$
S11	$3.11^{b} \pm 0.01$	$2.05^{ab} \pm 0.02$	$18.16^{i} \pm 0.02$	$13.55^{h} \pm 0.01$	$3.16^{f} \pm 0.01$	$63.13^{b} \pm 0.02$
S12	$3.12^{b} \pm 0.03$	$2.03^{a} \pm 0.01$	$18.37^{j} \pm 0.03$	$13.52^{g} \pm 0.02$	$3.15^{f} \pm 0.01$	$62.96^{a} \pm 0.02$
Control	$3.33^{C} \pm 0.05$	0.82 ± 0.01	9.99 ± 0.02	9.45 ± 0.01	1.30 ± 0.01	73.42 ± 0.02

[a] Values are means ± SD of triplicates. Different superscripts in the same column indicate a significant difference at the 95% confidence level; control: crackers developed from refined wheat flour.

decreased proportion of potato flour. This may be attributed to lower ash content in SPDF (3.37%) which may have been due to leaching out of minerals into the soaking water during sprouting of paheli dal. The composite flour crackers contained around 300% more ash than refined WF crackers (0.82%).

Composite flour containing higher SPDF showed significantly ($p < 0.05$) higher fiber content with a range of 1.55 to 3.19%. This may have been due to the almost five times higher fiber content in SPDF (5.05%) as compared to CTF. Compared to refined wheat flour crackers (1.30%), CTF and SPDF composite flour crackers provided 19.23–145% more fiber. The carbohydrate content in all composite flour samples was found to be in the range of 62.96 to 70.37%. Refined wheat flour crackers showed carbohydrate content of 73.42%. As compared to composite flour crackers, refined wheat flour crackers had more carbohydrate content. It can be observed that carbohydrate content decreased with a decrease in chayote tuber flour content which was found to be in line with the observation reported by Bazaz *et al.*,[37] for weaning food prepared from sprouted green gram flour and potato flour.

3.7 Ascorbic acid content, total phenolic content and antioxidant activity of crackers

The values of chemical analysis of crackers are listed in Table 5. The ascorbic acid content, total phenolic content and antioxidant activity of all composite flour crackers increased significantly ($p < 0.05$) from 0.87 to 1.39 mg/100 g, 279.46 to 313.35 mg GAE/100 g and 16.85 to 22.47%, respectively, with the increase in SPDF content from 30% to 50%. The degree of increase in ascorbic acid content, total phenolic content and antioxidant activity of composite flour crackers was 34.3%, 10.81% and 24.78%, respectively, with an increase in SPDF content from 30% to 50%. This may be attributed to higher ascorbic acid content, total phenolic content and antioxidant activity in SPDF. The germination process alters the antioxidant activity of the pulses as a result of change in phenolic content, enzyme activity, and mineral and vitamin content.[41] These observations corroborate those reported by Polat *et al.*,[7] and Venkatachalam and Nagarajan.[53] Sharma and Gujral[54] reported that continuous baking could alter the chemical structure of phenolic compounds, particularly by polymerization, and thereby reduce their extractable polyphenol content. The studies revealed that the developed composite flour crackers were nutritionally rich compared to refined wheat flour crackers.

3.8 Acidity of extracted fat of crackers and acid insoluble ash of crackers

The acidity of extracted fat and acid insoluble ash contents of all composite flour crackers decreased significantly ($p < 0.05$) from 1.19 to 1.00% and 0.036% to 0.014%, respectively, with an increase in SPDF content. Refined wheat flour crackers showed 1.20% acidity of extracted fat and 0.05% acid insoluble ash. Composite flour crackers with low SPDF substitution had significantly ($p < 0.05$) lower acidity (15.6%) of extracted fat and lower acid insoluble ash (61.11%) with an increase in SPDF level from 30% to 50%. The acidity of extracted fat and acid insoluble ash contents from the developed crackers were well within 1.2% (the upper limit) and 0.05% (the upper limit), respectively, as prescribed in IS (1011 : 2002).[31]

3.9 Hardness and spread ratio of crackers

Hardness of the cracker samples was estimated from the force–time plots obtained from compression tests. The hardness of all composite flour crackers increased significantly ($p < 0.05$) from 7.11 N to 12.29 N with the decrease in CTF content (Table 6). The control refined wheat flour cracker showed a hardness of 10.20 N. The higher level SPDF incorporation in composite flour showed a significant ($p < 0.05$) increase in hardness by 41.25%. The increase in hardness of crackers with increasing SPDF levels is supported by Polat *et al.*,[7] Venkatachalam and Nagarajan,[53] and Noor Aziah *et al.*,[55] who also reported increased hardness in legume-enriched crackers.

The spread ratio is regarded as one of the most important quality characteristics of biscuits/crackers since it influences texture, grain finesse, bite, and overall mouthfeel. Based on changes in diameter and thickness of crackers, the spread ratio

Table 5 Chemical analysis of crackers[a]

Sample	Ascorbic acid (mg/100 g)	Total phenolic content (mg GAE/100 g)	Antioxidant activity (%)	Acid insoluble ash (%)	Acidity of the extracted fat (%)
S1	$0.87^{b} \pm 0.06$	$280.16^{a} \pm 0.8$	$16.90^{b} \pm 0.6$	$0.036^{e} \pm 0.002$	$1.19^{ef} \pm 0.002$
S2	$0.93^{bc} \pm 0.06$	$279.99^{a} \pm 0.9$	$17.27^{bc} \pm 0.3$	$0.036^{e} \pm 0.001$	$1.17^{ef} \pm 0.001$
S3	$0.91^{bc} \pm 0.02$	$279.63^{a} \pm 0.3$	$17.27^{bc} \pm 0.3$	$0.036^{e} \pm 0.001$	$1.19^{f} \pm 0.010$
S4	$0.90^{b} \pm 0.10$	$279.46^{a} \pm 0.5$	$16.85^{b} \pm 0.3$	$0.036^{e} \pm 0.001$	$1.17^{e} \pm 0.010$
S5	$0.99^{e} \pm 0.00$	$287.66^{b} \pm 0.7$	$17.74\ ^{cd} \pm 0.8$	$0.034^{e} \pm 0.002$	$1.13^{d} \pm 0.002$
S6	$1.11^{d} \pm 0.02$	$295.25^{c} \pm 0.6$	$19.49^{f} \pm 0.2$	$0.030^{d} \pm 0.001$	$1.12^{d} \pm 0.020$
S7	$1.11^{d} \pm 0.02$	$295.07^{c} \pm 0.8$	$18.31^{de} \pm 0.5$	$0.030^{d} \pm 0.001$	$1.12^{d} \pm 0.000$
S8	$1.10^{d} \pm 0.00$	$294.99^{c} \pm 1.2$	$18.74^{e} \pm 0.4$	$0.030^{d} \pm 0.001$	$1.12^{d} \pm 0.000$
S9	$1.20^{c} \pm 0.02$	$303.72^{d} \pm 0.9$	$19.92^{f} \pm 0.2$	$0.023^{c} \pm 0.001$	$1.10^{c} \pm 0.003$
S10	$1.31^{fg} \pm 0.02$	$309.10^{e} \pm 0.5$	$22.13^{g} \pm 0.0$	$0.017^{b} \pm 0.001$	$1.02^{b} \pm 0.020$
S11	$1.30^{f} \pm 0.02$	$313.35^{f} \pm 1.4$	$22.47^{g} \pm 0.0$	$0.014^{a} \pm 0.001$	$1.00^{a} \pm 0.030$
S12	$1.39^{g} \pm 0.10$	$309.63^{e} \pm 0.3$	$22.02^{g} \pm 0.4$	$0.014^{a} \pm 0.001$	$1.00^{a} \pm 0.020$
Control	$0.00^{a} \pm 0.00$	$356.00^{g} \pm 1.0$	$12.05^{a} \pm 0.02$	$0.050^{f} \pm 0.001$	$1.20^{f} \pm 0.001$

[a] Values are means ± SD of triplicates. Different superscripts in the same column indicate a significant difference at the 95% confidence level.

and percent spread changed as well. The spread ratio of crackers of all composite flour crackers decreased significantly ($p < 0.05$) by 19.9% from 17.34 to 9.88 with the decrease in CTF content. Refined wheat flour crackers showed a spread ratio of 6.58 which was lower than that of composite flour crackers. According to McWatters,[56] the reduced spread ratio of crackers containing gluten-free composite flour may be due to the fact that composite flour tends to form aggregates with more hydrophilic sites that compete with the dough's limited free water. Oluwamukomi *et al.*[57] and Jothi *et al.*[58] reported a comparable trend of decrease in spread ratio with the decreased cassava flour in wheat-cassava composite biscuit enriched with soy flour and decrease wheat and potato flour, respectively.

3.10 Color of composite flour crackers

The color of foods gives an indication of their quality, especially in bakery products like crackers. The data obtained for the color value of the composite flour crackers are shown in Table 6. The color parameters *viz.*, L^* (lightness), a^* (redness) and b^* (yellowness) values were in the range of 35.20–50.91, 2.40–5.30 and 15.13–18.60, respectively. Refined wheat flour crackers showed an L^* (lightness) value of 75.50, a^* (redness) value of 2.56, and b^* (yellowness) value of 26.51. The redness of composite flour crackers was found to be higher than that of refined wheat flour crackers. A significant decrease ($p < 0.05$) in the L^* value was observed when the SPDF ratio increased. The lightness and yellowness value of composite flour crackers increased with the increase in CTF percent whereas redness of composite flour samples increased with an increase in SPDF and decrease in CTF. The presence of SPDF had significant effects on the redness (a^*) of the crackers; this coordinate reflects the degree of browning on a baked surface and should be higher for brown surfaces. This implies that the SPDF in the crackers may boost the protein availability for Maillard reactions when baking. The hue angle and chroma of composite flour crackers were in the range of 70.91 to 82.46° and 15.91 to 18.69, respectively; however, refined wheat flour crackers had 84.50° and 26.63° hue angle and chroma, respectively. These values were higher than those of CTF–SPDF crackers, indicating a more intense/rich color for control crackers.

Table 6 Physical analysis of crackers of composite flour blends and refined wheat flour[a]

Sample	Hardness	Spread ratio	L^*	a^*	b^*	Chroma	Hue angle (°)
S1	$7.22^{ab} \pm 0.03$	$17.13^{g} \pm 0.00$	$49.21^{f} \pm 0.66$	$2.45^{a} \pm 0.12$	$17.64^{f} \pm 0.23$	$17.81^{e} \pm 0.24$	$82.14^{f} \pm 0.3$
S2	$7.12^{a} \pm 0.02$	$17.29^{h} \pm 0.01$	$49.77^{f} \pm 0.00$	$2.48^{a} \pm 0.23$	$18.53^{g} \pm 0.18$	$16.91^{d} \pm 0.01$	$81.87^{f} \pm 0.02$
S3	$7.29^{b} \pm 0.01$	$17.34^{h} \pm 0.01$	$49.30^{f} \pm 0.01$	$2.40^{a} \pm 0.01$	$18.60^{g} \pm 0.25$	$16.50^{c} \pm 0.02$	$79.43^{e} \pm 0.2$
S4	$7.11^{a} \pm 0.02$	$17.30^{h} \pm 0.03$	$50.91^{g} \pm 0.40$	$2.45^{a} \pm 0.02$	$17.82^{f} \pm 0.06$	$15.99^{a} \pm 0.01$	$72.64^{b} \pm 0.1$
S5	$7.83^{c} \pm 0.03$	$16.50^{f} \pm 0.30$	$43.34^{e} \pm 0.00$	$3.04^{b} \pm 0.06$	$16.22^{e} \pm 0.03$	$16.13^{a} \pm 0.21$	$77.24^{d} \pm 0.2$
S6	$9.30^{e} \pm 0.26$	$15.55^{e} \pm 0.05$	$42.58^{d} \pm 0.01$	$3.53^{c} \pm 0.01$	$15.83^{d} \pm 0.01$	$16.22^{abc} \pm 0.01$	$77.46^{d} \pm 0.03$
S7	$8.72^{d} \pm 0.02$	$15.16^{d} \pm 0.01$	$43.32^{e} \pm 0.00$	$3.57^{c} \pm 0.10$	$15.59^{c} \pm 0.05$	$16.37^{bc} \pm 0.02$	$75.61^{c} \pm 0.2$
S8	$8.81^{d} \pm 0.03$	$15.21^{d} \pm 0.03$	$42.58^{d} \pm 0.01$	$3.56^{c} \pm 0.04$	$15.51^{c} \pm 0.17$	$15.92^{a} \pm 0.20$	$71.92^{b} \pm 1.3$
S9	$10.27^{f} \pm 0.03$	$12.51^{c} \pm 0.05$	$40.57^{c} \pm 0.12$	$4.08^{d} \pm 0.05$	$15.46^{bc} \pm 0.02$	$15.91^{a} \pm 0.16$	$77.12^{d} \pm 0.3$
S10	$12.29^{i} \pm 0.01$	$9.97^{a} \pm 0.01$	$35.45^{a} \pm 0.92$	$4.89^{e} \pm 0.29$	$15.13^{a} \pm 0.08$	$17.56^{e} \pm 0.39$	$82.46^{f} \pm 0.9$
S11	$12.10^{h} \pm 0.10$	$9.88^{a} \pm 0.01$	$36.95^{b} \pm 0.01$	$4.78^{e} \pm 0.02$	$15.25^{ab} \pm 0.03$	$18.69^{f} \pm 0.21$	$82.43^{f} \pm 0.7$
S12	$11.65^{g} \pm 0.03$	$10.78^{b} \pm 0.01$	$35.20^{a} \pm 0.71$	$5.30^{f} \pm 0.06$	$15.27^{ab} \pm 0.02$	$16.16^{ab} \pm 0.04$	$70.91^{a} \pm 0.2$
Control1	10.20 ± 0.02	6.58 ± 0.02	$75.50^{h} \pm 0.10$	$2.56^{a} \pm 0.02$	$26.51^{h} \pm 0.04$	$26.63^{g} \pm 0.04$	$84.50^{g} \pm 0.1$

[a] Values are means ± SD of triplicates. Different superscripts in the same column indicate a significant difference at the 95% confidence level.

3.11 Sensory evaluation of composite flour crackers

In the development of gluten-free food, achieving appropriate sensory properties is a significant task. The appearance, flavour, aroma, mouth feel, crispiness and overall acceptability of the crackers made from composite flour, refined wheat flour and market samples were evaluated using a 9-point hedonic scale. The sensory indices were calculated as explained in Section 2.6.8 and Fig. 2 shows the impact of the sensory qualities of crackers. There was a significant difference in preferences for the appearance of composite flour crackers. The sensory indices for the appearance of crackers of all composite flour ranged from 45.19 to 54.81. Refined wheat flour crackers had an appearance index of 60.00 while market crackers scored 60.74. Composite flour crackers scored lower than refined wheat flour crackers and market crackers in appearance which may be attributed to more Maillard's browning in composite crackers containing SPDF. The flavor preferences of composite flour crackers varied significantly. The sensory indices for the flavour of crackers developed from composite flour ranged from 46.17 to 54.32 while refined wheat flour crackers scored 60.74 and market crackers scored 61.48. The lower scores of the flavor index in composite flour crackers suggest that the flavor of SPDF in crackers might be less liked by the panels as the judges were not familiar with pulse-based crackers. The aroma indices of CTF–SPDF crackers ranged from 47.41 to 51.11. The preferences for the aroma among the composite flour crackers varied significantly. Refined wheat flour crackers scored 60.49 while market crackers scored 61.23. Both these crackers scored higher than CTF–SPDF crackers which may be due to the fact that addition of SPDF might have developed some aroma in crackers which was not liked by the judges.

Textural characteristics, *viz.*, crispiness and mouthfeel, are good indicators of the freshness of baked crackers.[57] Mouthfeel of the crackers represents structural and mechanical changes during chewing and swallowing of the baked product, as a result of the intrinsic characteristics and composition of the food.[58] The sensory indices for the mouthfeel of crackers of all composite flour ranged from 45.93 to 53.33. The preferences for the mouthfeel varied significantly among the composite flour crackers. Refined wheat flour crackers scored 60.49 while market crackers scored 61.23 in mouthfeel. The composite flour crackers showed lower mouthfeel scores than market and refined wheat flour crackers which may be due to addition of SPDF in the composite flour crackers. The preferences for crispiness among the composite flour crackers differed significantly. The sensory indices for the crispiness of crackers of all composite flour ranged from 45.68 to 55.06. Refined wheat flour crackers scored 60.00 while market crackers scored 60.74 in crispiness index which were higher than the score of the composite flour crackers. This may indicate that addition of chayote tuber flour might have slightly reduced the crispiness of the baked crackers. Both mouthfeel and crispness scores increased with increasing portion of SPDF up to 40% and then

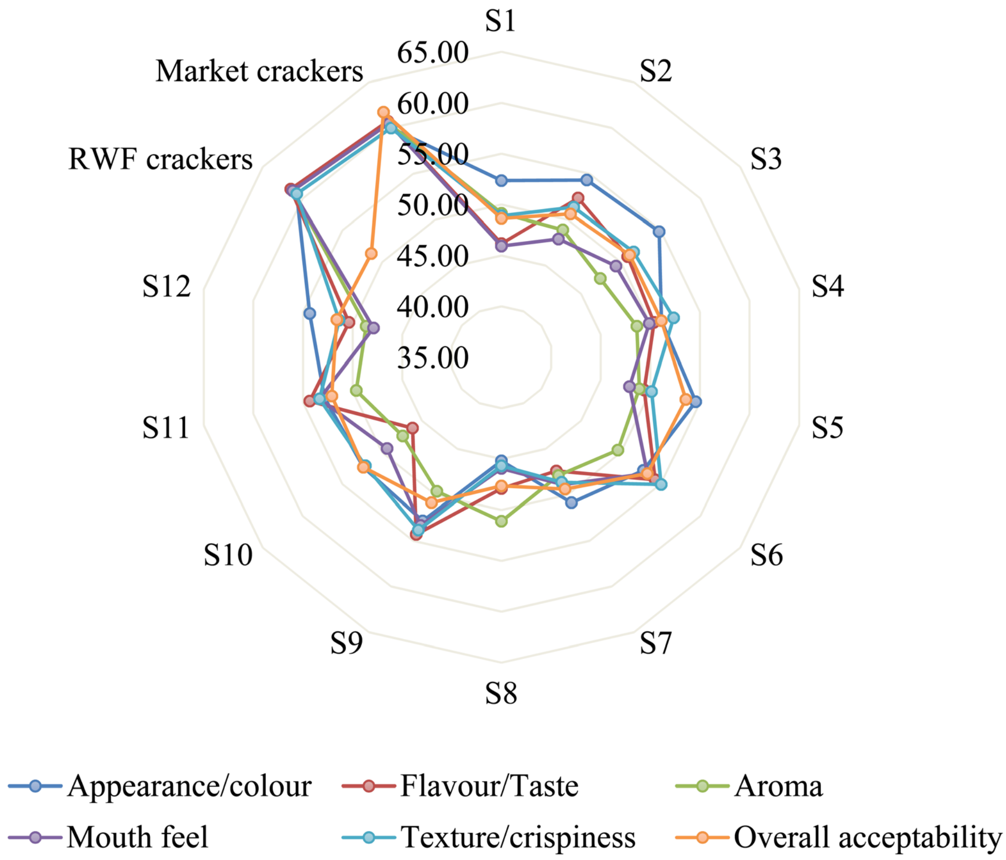

Fig. 2 Variation in sensory indices of developed composite flour crackers.

reduced. This indicated that higher levels of pulse/paheli dal flour addition adversely affected the textural properties.[59,60]

The sensory indices for the overall acceptability of crackers developed from composite flour ranged from 47.65 to 53.33. The preferences for the overall acceptability varied significantly among the composite flour crackers. Refined wheat flour crackers had an overall acceptability index of 51.36 which is similar to that of composite flour crackers whereas market crackers scored a higher value of 61.73. From these overall acceptability index values, it may be inferred that chayote tuber flour-sprouted paheli dal flour crackers were well received by the judges and their quality is comparable to that of refined wheat flour crackers.

3.12 Model fitting and optimization

For optimization of the composite flour formulation for production of good quality crackers, three parameters/responses based on the Bureau of Indian Standards (BIS) and one of each from textural, sensory and physical properties namely moisture content (Y_1), acid insoluble ash (Y_2), acidity of the extracted fat (Y_3), hardness (Y_4), spread ratio (Y_5) and overall acceptability, *OAA* (Y_6) were selected. Optimization was performed for twelve cracker formulations (S1–S12) made from composite flours. The experimental responses of these selected composite flour crackers were modeled using regression models in terms of two independent variables (*viz.* CTF (X_1) and SPDF (X_2)) using Design Expert 13.0.

For prediction of moisture content, acid insoluble ash, acidity of the extracted fat, hardness, spread ratio and overall acceptability values of composite flour crackers in terms of flour formulation, the values were fitted to linear (Y_1), quadratic (Y_2, Y_4 and Y_5), cubic model (Y_3) and quartic model (Y_6), respectively, as shown in eqn (8)–(13). The generated models in terms of real values are as follows.

$$Y_1 = 5.763X_1 + 0.449X_2 \tag{8}$$

$$Y_2 = 0.024X_1 - 0.116X_2 + 0.251X_1X_2 \tag{9}$$

$$\begin{aligned} Y_3 = 4.834X_1 - 13.685X_2 + 21.728X_1X_2 \\ - 31.68X_1X_2(X_1 - X_2) \end{aligned} \tag{10}$$

$$Y_4 = 11.08X_1 + 50.99X_2 - 74.29X_1X_2 \tag{11}$$

$$Y_5 = 6.19385X_1 - 58.46723X_2 + 145.13461X_1X_2 \tag{12}$$

$$\begin{aligned} Y_6 = 839.865X_1 + 4719.16X_2 - 11090.54X_1X_2 \\ + 7591.69X_1X_2(X_1 - X_2) - 9089.861X_1X_2(X_1 - X_2)^2 \end{aligned} \tag{13}$$

The ANOVA and fit statistics of the fitted model for moisture content, acid insoluble ash and acidity of the extracted fat are shown in Table 7. The developed models were statistically significant ($p < 0.001$), indicating that it was a good fit. From the ANOVA and model fit statistics, the coefficient of determination (R^2) was higher (>0.9) for most of the models developed. The lack of fit was found to be insignificant, indicating that the model was a good fit. The adjusted R^2 also showed <0.2 difference from the predicted R^2. Adequate precision values of >4 and coefficient of variation (CV) of <10% of these models show the adequacy of the developed models. From these model fit statistics, all the developed models indicated an adequate signal and were suitable to navigate the design space.

3.13 Optimization and validation of responses

A simple lattice mixture design with twelve flour formulations of CTF and SPDF was generated using Design Expert software (version 13.0). The developed models (as discussed in Section 3.12) for moisture content, acid insoluble ash content, acidity of extracted fat, hardness, spread ratio and overall acceptability were used to predict these responses and thereby optimize the composite flour formulation of crackers based on these parameters. The optimization criteria fixed to determine the optimum cracker formulation were moisture content (0 to 5%) BIS (IS1011-2002), acid insoluble ash (0–0.05%) BIS (IS1011-2002), acidity of the extracted fat (0–1.2%) BIS (IS1011-2002), maximum hardness,[30] maximum SR,[30] and maximum OAA.[12]

As a result of numerical optimization using the desirability function with the above criteria, the Design Expert software produced four appropriate solutions for the optimized formulation. Based on the 4-solution evaluation, the formulation with the highest desirability of 0.743 was selected as the optimum solution for the production of composite flour crackers from 61.22% CTF and 38.78% SPDF. High desirability values (as compared to other solutions) indicate acceptable process parameters for achieving favorable quality of crackers. In the selected optimized solution, the spread ratio was higher

Table 7 Model fit statistics for moisture content, acid insoluble ash, acidity of the extracted fat, hardness, spread ratio and overall acceptability

Source	Moisture content	Acid insoluble ash	Acidity of the extracted fat	Hardness	Spread ratio	Overall acceptability
Model significance	Significant	Significant	Significant	Significant	Significant	Significant
R^2	0.985	0.984	0.99	0.993	0.990	0.731
Adj. R^2	0.988	0.985	0.986	0.991	0.987	0.578
Pred. R^2	0.9853	0.9799	0.9799	0.9864	0.9813	NA
p-Value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0358
F-Value	940.36	1291.63	384.08	627.93	450.15	4.76
% CV	1.28	2.12	3.19	1.97	2.24	3.07
Lack of fit	1.72 (NS)	0.1884 (NS)	0.0273 (NS)	0.0056 (NS)	1.93 (NS)	
SD	0.0472	0.0006	0.0009	0.1793	0.3256	0.2093
PRESS	2.10	0.0009	0.0526	43.29	95.43	0.8343
Adequate precision	55.1632	73.6384	40.7616	53.8838	43.7800	7.0742

Table 8 Predicted and actual values of moisture content, acid insoluble ash, acidity of extracted fat, hardness, spread ratio and overall acceptability

Dependent variables	Predicted	Actual	RPE%
Moisture content, % wb	3.71	3.80 ± 0.1	2.53%
Acid insoluble ash content, % db	0.030	0.032 ± 0.01	6.67%
Acidity of the extracted fat, % oleic acid	1.123	1.127 ± 0.01	0.35%
Hardness, N	8.57	9.03 ± 0.1	5.36%
Spread ratio	15.58	16.00 ± 1.5	2.76%
Overall acceptability	7.02	7.20 ± 1.4	2.58%

whereas hardness and acid insoluble ash were lower than other solutions which had 50% CTF and 50% SPDF. These values signify a more desirable texture characterized by improved crispness and brittleness of gluten-free crackers with high nutritional value. In addition, higher CTF and lower SPDF formulation would also be more cost-effective than formulations prepared at an equal ratio as the chayote tuber, being a locally available and underutilized crop, is relatively inexpensive compared to paheli dal, which involves additional costs associated with soaking, sprouting, drying, and milling. Based on these criteria, the optimized formulation of 61.22% CTF and 38.78% SPDF for composite flour crackers was selected as a more economically viable alternative for commercial production, particularly in small and medium-scale bakery industries. The predicted quality parameters of the composite flour crackers with the optimized formulation were: 3.71% moisture content (w.b.), 0.030% acid insoluble ash, 1.123% acidity of the extracted fat, 8.57 N hardness, 15.58 spread ratio and 7.02 overall acceptability.

To validate the optimization results, composite flour crackers were prepared in triplicate using the recommended optimized formulation. The quality of these crackers was analyzed and compared with the predicted responses. In order to compare predicted and experimental responses, relative percent error (RPE) was calculated using eqn (14).[61] An RPE value less than 10% indicates that the selected model is well fitted.[62]

$$\mathrm{RPE}\% = \frac{\text{actual value} - \text{predicted value}}{\text{predicted value}} \times 100 \tag{14}$$

Based on the optimized cracker formulation, Table 8 records the predicted and actual moisture content, acid insoluble ash content, acidity of the extracted fat, hardness, spread ratio, and overall acceptability of crackers. For the optimized cracker formulation, the relative percent errors between the actual and predicted responses for moisture content, acid insoluble ash content, acidity of extracted fat, hardness, spread ratio and overall acceptability were 2.53%, 6.67%, 0.35%, 5.36%, 2.76% and 2.58%, respectively. All of the relative percent errors were below 10% which indicates that the developed models were suitable for predicting the quality of CTF–SPDF crackers.

3.14 Quality of optimized chayote tuber flour-sprouted paheli dal flour crackers

Composite flour crackers were developed using optimized formulations of 61.22% CTF and 38.78% SPDF. From 1 kg of chayote tuber, about 0.25 kg of chayote tuber flour was produced. Using this amount of chayote flour and the corresponding optimized proportion of SPDF, about 0.43–0.45 kg of composite flour crackers was produced. This indicates a 43–45% cracker yield based on 1 kg of chayote tuber. The quality of the crackers developed using the optimized formulation was determined in terms of proximate composition, fiber content, acid insoluble ash content, and acidity of extracted fat. The results of these quality parameters are shown in Table 9. The optimized composite flour crackers contained 3.72% w.b. moisture content, 2.7% ash content, 11.53% fat content, 2.3% fiber content, 15.78% protein content and 63.97% carbohydrate content. The acid insoluble ash content and acidity of the extracted fat were found to be 0.032% and 1.12% oleic acid, respectively. The moisture content of developed crackers was less than values (6.46–8.78% w.b.) reported by ref. 63 for gluten-free crackers made from germinated pearl millet + defatted sesame + defatted tigernut. The ash content (2.7%) is on par with or slightly higher than 2.4% as reported for many composite gluten-free crackers (germinated pearl millet,

Table 9 Quality of composite flour crackers and BIS standards for snack crackers

Quality parameters	Composite flour crackers	BIS standards for biscuits	FSSAI standards for biscuits
Moisture content, % wb	3.72	5 (maximum)	
Fat content, %	11.53	—	—
Ash content, %	2.70	—	—
Protein content, %	15.78	—	—
Fiber content, %	2.30	—	—
Carbohydrate content, %	63.97	—	—
Acid insoluble ash content, % db	0.030	0.05 (maximum)	0.1
Acidity of the extracted fat, % oleic acid	1.123	1.2 (maximum)	2

defatted sesame and defatted tigernut) by ref. 63. This indicates good mineral content. This could reflect beneficial mineral contribution from chayote tuber flour. The developed crackers (15.78%) have a higher protein content than many other gluten-free crackers reported in the literature, *e.g.*, the pearl-millet/sesame/tigernut crackers (max ∼12.2%).[63] This suggests the SPDF (sprouted pulse dal flour) is contributing strongly to improving the protein density, which is a nutritional benefit especially for gluten-free formulations that often suffer from low protein. The fiber content (2.3%) of the developed cracker is slightly lower than that of the pearl-millet/sesame/tigernut crackers (3.6–4.2%).[63] In a study of crackers from sprouted multigrain flours (quinoa, millet, fenugreek, *etc.*), crude protein was in the range of 7.29–8.31%, fat ∼8.36–14.28%, ash ∼2.21–2.40%, and fiber ∼1.24–1.75%, depending on the blend.[64] The optimized chayote–SPDF crackers have high protein, good mineral content, low moisture (which is good for crispness), and moderate fat content, all of which compare very favorably with many gluten-free cracker formulations in the literature.

No standards are available for vegetable crackers. Since crackers are also a type of biscuit, the quality of the developed composite flour crackers with the optimized formulation was compared with BIS and Food Safety and Standards Authority of India (FSSAI) standards for wheat flour biscuits. The moisture content was found to be lower than 5% w.b. as recommended in BIS standards for wheat flour biscuits. In addition to that, both the values of acid insoluble ash content and acidity of extracted fat were found to be lower than the values recommended in BIS[31] and FSSAI[65] standards for biscuits. Hence, it can be inferred that good quality CTF–SPDF composite flour crackers can be produced which conforms to both BIS and FSSAI standards.

4. Conclusions

The present study demonstrates the successful development of gluten-free crackers utilizing composite flours derived from chayote tuber flour and sprouted paheli dal flour. The incorporation of SPDF into CTF significantly enhanced the nutritional profile of the crackers, achieving up to 58.11% higher protein content and 76.92% more fiber compared to traditional refined wheat flour crackers. Additionally, the composite flour exhibited improved functional properties, including increased foaming capacity and stability, which are crucial for the desired texture and quality of baked goods. The optimum formulation, comprising 61.22% CTF and 38.78% SPDF, yielded crackers with a balanced nutritional composition, aligning with the standards set by the BIS and the FSSAI. These findings underscore the potential of utilizing underutilized crops like chayote tubers and indigenous legumes such as paheli dal in developing value-added, health-oriented gluten-free products. In addition to the enhanced nutritional and functional properties, the developed composite flour crackers offer meaningful sustainability benefits. The reliance on locally available, low-input crops such as chayote tubers and paheli dal reduces water and fertilizer requirements, thereby lowering the environmental footprint of raw material production. Transforming chayote tubers into flour not only mitigates post-harvest losses but also adds value to an underutilized crop, contributing to waste reduction and circular resource use. Furthermore, local sourcing strengthens rural economies and minimizes energy expenditure associated with long supply chains. The resulting shelf-stable crackers require minimal storage energy, reinforcing the overall eco-efficiency of the product. In conclusion, these sustainability advantages establish a viable approach for producing nutritionally enriched, gluten-free crackers that not only cater to individuals with gluten sensitivities but also contribute to the valorization of local agricultural resources. The adoption of such formulations can promote dietary diversification and support sustainable agricultural practices, offering a promising avenue for the development of functional foods in the gluten-free market.

Author contributions

Robishini Akoijam: conceptualization, methodology, visualization, investigation, software, data curation, formal analysis, writing – original draft. Dhamchoe Dolma Bhutia: writing – review & editing, formal analysis. Sujata Jena: conceptualization, resources, project administration, supervision, writing – review and editing. Prashant Pandharinath Said: writing – review & editing, formal analysis.

Conflicts of interest

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

Data availability

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

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