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Unlocking the potential of rice bran through extrusion: a systematic review†

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Rice bran (RB) is a by-product of the rice milling process and is rich in nutrients and bioactive compounds making it a valuable ingredient for extruded foods. Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) was applied that involved screening large databases (Google Scholar, PubMed, Web of Science, ScienceDirect and Scopus) and analysing the most relevant peer-reviewed forty-four journal articles. This review discusses the benefits of incorporating RB into various food product formulations, including meat analogues, biscuits, cookies, cakes, noodles, breads, and pasta. The review also examines how extrusion conditions, such as temperature, screw speed, and moisture content affect the physicochemical parameters of the expanded extrudates from the feed formulation incorporated with RB. In extrusion, 0–30% RB was used as feed in 52.27% of the studies, and 71.42% of the studies used screw speed below 250 rpm. Almost all studies had extrusion temperatures below 150 °C, and plant-based meat used a higher moisture content (60–70%) during extrusion. The extrusion of RB results in increased hardness and bulk density, and reduced expansion. However, depending on the feed's composition, moisture content, extrusion temperature, and screw speed, its addition to the feed mixture could cause variability of results for the water solubility index (WSI), water absorption index (WAI), thermal behaviour and viscosity. RB in foods processed through extrusion enhances their nutritional profiles, especially total phenolics, antioxidant activity, and functional properties and supports sustainable practices. Overall, the use of RB in food extrusion holds promise for the development of nutritious, functional, and sustainable food products.

Sustainability spotlight

Rice bran (RB) has immense potential as a sustainable food source, contributing to food security, environmental health, and responsible resource management. It can be extruded to get snacks fortified with vitamins, minerals, and protein. It can be used as an ingredient in baked goods, meat alternatives, and even pasta, reducing reliance on other ingredients. The possibilities are endless for catering to every palate and meal occasion. Food waste can be minimized, diverting a valuable resource from landfills, which aligns with the growing demand for sustainable food systems. The application of extrusion in RB aligns perfectly with the principles of a circular economy, where food waste and by-products are recovered and valorized. This reduces waste generation and creates new revenue streams for rice producers and processors. RB extrusion contributes to sustainable intensification by maximizing resource utilization and minimizing environmental impact. The process requires less water and energy reducing the environmental footprint of food production. Additionally, extruded rice bran offers enhanced digestibility and nutrient bioavailability, improving feed efficiency and reducing reliance on resource-intensive animal protein sources. This aligns with the United Nations Sustainable Development Goal 1 (no poverty) by creating affordable food, Goal 2 (zero hunger) by improving food security, Goal 3 (good health and well-being) by enhancing bioactive compounds, and Goal 12 (responsible consumption and production) by valorizing a by-product.

1. Introduction

Rice (*Oryza sativa* L.) serves as the primary staple food for most Asian populations, with an estimated 50% of the global population relying on it for 70% of their calorific intake.[1] In the crop year 2022, rice cultivation spanned 165.25 million hectares globally,[2] producing 725.56 million metric tons by the top 20 countries.[3] Projections indicate production of approximately 513.5 million metric tons of milled rice for 2023/24.[4] Considering an average rice bran (RB) yield of 8%,[5] approximately 44.65 million metric tons of RB will be produced in 2023/24. The defatted bran yield, accounting for oil fractions ranging from 14 to 18%,[5] is anticipated to be between 36.61 and 38.40 million metric tons in 2023/24.

Historically, RB has been used as waste or animal feed in developing countries.[6] However, recent times have seen RB gaining importance due to its diverse applications, such as in producing edible oil, biofuels, cosmetics, and soaps. RB, a by-product of rice milling, is known for its high nutritional value, containing components such as fat (15–20%), protein (11–20%),

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total fibre (20–40%) and total ash (7–12%)[7,8] which vary based on paddy variety, agronomic practices, and processing methods.[9] The amino acid profile of RB protein (RBP) is supposed to be better than that of casein and contains more aspartic acid, glycine, arginine, alanine, cysteine, and histidine alongside comparable quantities of threonine and valine,[10] contributing to its nutritional and functional values. Moreover, RB is a source of micronutrients, like tocopherols, tocotrienols, oryzanols, β-sitosterol, and phytosterols, which exhibit antioxidant properties.[11] RB has been linked to reducing the risk of heart diseases and atherosclerosis,[12] and shown to exhibit anticancer and anti-hyperlipidemic effects[13] and laxative effects.[14] It has even been found to promote hair growth by inhibiting 5-alpha-reductase, an enzyme that converts testosterone to dihydrotestosterone,[13] and to possess antitumor properties due to momilactones.[15] The latter also exhibit inhibitory effects on pancreatic α-amylase and α-glucosidase, indicating potential benefits for diabetes and skincare.[16] Given these attributes, RB is gaining significance for food processors in various processed foods.

RB oil contains a substantial portion of polyunsaturated fatty acids like linoleic acid and linolenic acid.[17] However, these fatty acids are susceptible to oxidation and rancidity due to the lipase activity and oxygen.[18] To ensure storage stability, different stabilization processes have been developed, with ultraviolet irradiation emerging as a practical choice for stabilizing bran oil, outperforming both heating methods (microwave heating, autoclaving, extrusion, steam heating, dry heating & infrared heating) and non-heating methods (enzyme treatment, ultrasound, and ultraviolet irradiation low-temperature treatment).[19,20] Additionally, extrusion treatment can deactivate lipase, thus enhancing RB functionality.

RB is getting substantial attention in the food industry due to its multiple benefits. Its application has been expanding since the history of utilising rice by-products dating back to 1903 when the Louisiana Agricultural Experiment Station documented rice oil and its by-products.[21] Over the years, various studies have explored the functional components and potential applications of RB.[22–24] Modern research in RB aims to address Sustainable Development Goals (SDGs) employing RB in producing meat analogues,[25] biscuits, cookies, cake,[26] noodles,[27] bread,[28] pasta[29] and extrudates.[30,31] This aligns with SDG's Goal 1 (no poverty) by creating affordable food, Goal 2 (zero hunger) by improving food security, Goal 3 (good health and well-being) by enhancing bioactive compounds and Goal 12 (responsible consumption and production) by valorising a by-product. So, the use of the RB's functional and phytochemical properties has led to its widespread adoption.

RB's potential for use in food extrusion is particularly notable. Its richness in dietary fibre, vitamins, minerals, and antioxidants makes it a valuable ingredient for extruded foods. Factors like extrusion temperature, screw speed, feed moisture, and composition significantly influence extrudate quality affecting lateral expansion (LE), bulk density (BD), water solubility index (WSI), water absorption index (WAI) and hardness.[30] Moreover, extrusion treatment can change protein structure,[25] viscosity, colour,[32] antioxidant activity,[33] nutritional components[34] and sensory attributes.[25] The incorporation of RB has been found to enhance the texture and sensory attributes of extruded snacks. Consequently, this review aims to explore the effects of extrusion conditions on the physicochemical parameters of the expanded extrudates employing RB and explore RB's application in various food systems.

2. Methodology

To conduct the literature review, we adopted the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) approach, which has gained prominence in agriculture and food science.[1,35] PRISMA's systematic process ensures unbiased and robust conclusions by systematically searching, appraising, and synthesising research evidence.[36]

RB has a wide range of potential applications in the food industry. Extrusion of RB can be used to modify its properties and make it suitable for use in a variety of products. By overcoming the challenges of using RB in extrusion, food manufacturers can develop healthy, nutritious, and affordable products that appeal to consumers.[25,33,34] So, substantial interest and related publications have only risen over the past decade. The search from Scopus and Web of Science represents the growing research in the field of extrusion of RB (ESI Fig. S1†). However, the review encompassed peer-reviewed journal articles from the five widely used scientific databases: Google Scholar, PubMed, Web of Science, ScienceDirect and Scopus. To address our focused research question on "rice bran extrusion", we employed the "AND" Boolean operators. Specifically, the search "rice bran" AND "extrusion" was executed on Google Scholar. The searches across all databases were updated on 26th April 2023. 3 additional relevant articles were added when updating in December 2023. Details, including search strings, weblinks and screenshots, are provided in the Supplementary material† (Table S1† and Plate 1). From PubMed, Web of Science, ScienceDirect and Scopus, 21, 171, 447 and 177 articles were identified, respectively. The Google Scholar search yielded 9010 articles but due to web restrictions, only 1000 articles were accessible. Although the primary search returned 9826 articles (Fig. 1a), not all were included in subsequent screening stages. Through a meticulous process involving duplicate removal and rigorous application of eligibility criteria, we refined the article selection eligibility criteria to encompass: (1) original research articles, (2) peer-reviewed English language articles (accounting for potential language discrepancies in titles and abstracts), (3) articles focusing on RB-containing feed extrusion and extruded RB, (4) availability of dependent variables data (feed composition, moisture, temperature, and screw speed) and (5) availability of the nutrient content, physicochemical parameters, and sensory analysis (or any of these parameters). Ultimately, 44 articles met these criteria and were included in the systematic review (Fig. 1a). The selected articles provided relevant data concerning dependent variables such as water solubility index, water absorption index, hardness, bulk density, and expansion. Key independent or input parameters include temperature, screw speed and moisture content of the feed, and the quantity of RB used in the extrusion process. An overview of the study's focus and methodology is succinctly summarized (Fig. 2).

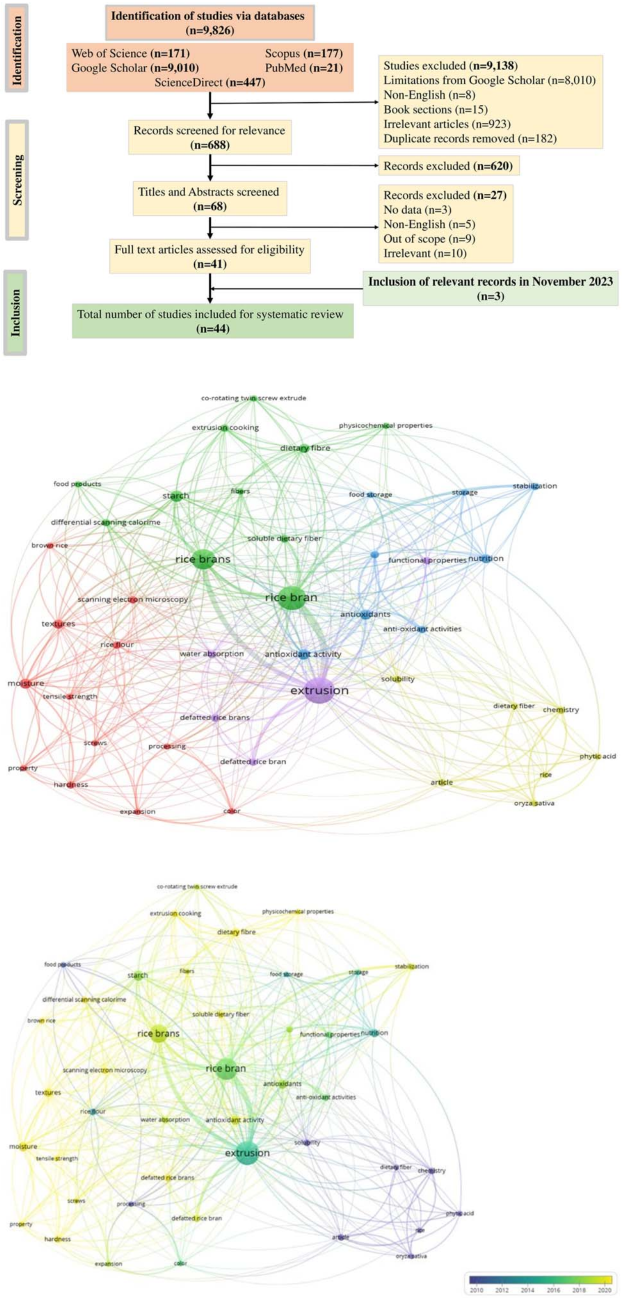

Fig. 1 (a) Selection of the articles using Preferred Reporting Items for Systematic reviews and Meta-Analysis. (b) Network visualization of 44 articles. (c) Overlay visualization of 44 articles.

3. Results and discussion

There are many papers dealing with RB extrusion. However, it is difficult to provide conclusive results because of variations in different process parameters (feed composition and type, level of moisture content, range of screw speed and temperature, and their combination), type of RB (defatted or raw or stabilized or methods of stabilization) and wide range of dependent variables measured. The heterogeneity is too high, and the studies are very dissimilar, so we conducted a systematic review with a narrative synthesis instead of a quantitative meta-analysis attempting to provide a general conclusion on the extrusion of RB and RB-incorporating foods. VOS viewer was used to identify the emerging trends and research gaps within 44 articles. This technique is used to create bibliometric networks like co-authorship, bibliographic coupling, and co-citation networks. Bibliographic files from different databases like Web of Science, Scopus, Dimensions, Lens, PubMed, Crossref, Europe PMC, OpenAlex Semantic Scholar, OpenCitations, and WikiData can be uploaded and visualized through network, density and overlay visualization. From the database, 368 keywords were extrapolated, but for the analysis, the occurrence threshold was set at a minimum of 3 among all the documents. Fig. 1b shows a word cloud relating to searched keywords. The number of times the provided keywords appear in literature records is shown by their font size. The core keywords (rice bran, rice brans, extrusion) and frequently used terms are “starch”, “antioxidants”, “dietary fibre”, “nutrition”, and “physicochemical qualities”. In Fig. 1c, the database keyword occurrence overlay is reported. It appears that more recently, the terms “extrusion cooking,” “dietary fibre,” and other terms related to the quality of extruded RB have gained much more attention in the scientific literature in the last few years. This is an important trend as the RB extrusions require more research to understand quality, health benefits and physicochemical properties.

Four different independent parameters are employed to review the effect on the RB extrudates and their products: (a) feed composition, (b) moisture content, (c) screw speed, (d) temperature. The independent variables were sub-grouped, and their values used in different experiments were included in the nearest range for frequency per cent. The use of RB in the extrusion study was sub-grouped into 0–30%, more than 31% and 100% where the frequency of use was 52.27%, 6.81% and 40.91%, respectively (Fig. 3a). Out of 44 studies, 7 articles (15.91%) mentioned that 100% of RB was extruded where their proportions were used in other food products. The frequency of using defatted RB (DRB), raw RB and stabilized RB (use of RB insoluble dietary fibre included in stabilized RB, Table 2, S. N. 3) was 29.55%, 43.18% and 11.36%, respectively in the extrusion experiments. There was no mention of the type of RB in 15.91% of the studies (Fig. 3b). Most studies mentioned extrusion temperatures below 150 °C. The use of moisture content was sub-grouped as 8–16%, 17–24%, 25–32%, 33–40% and 60–70% where the frequency of use in the extrusion was 25.00%, 37.50%, 21.88%, 6.25% and 9.38% respectively (Fig. 3c). Plant-based meat analogues used the higher moisture content in extrusion. The use of screw speed was sub-grouped <250 RPM, 250–500 rpm and >500 RPM. The frequency of use in the extrusion was 71.43%, 25.71%, and 2.85%, respectively (Fig. 3d). For general comparison, expansion, density, hardness, WAI, WSI, total phenolics and antioxidant activity were considered, while almost all the articles suggest a decrease in expansion and an increase in other parameters due to RB extrusion. Extrusion processing involves subjecting raw materials to heat, pressure, and mechanical shear forces, resulting in transformative effects.[30,31] Raw materials are combined with

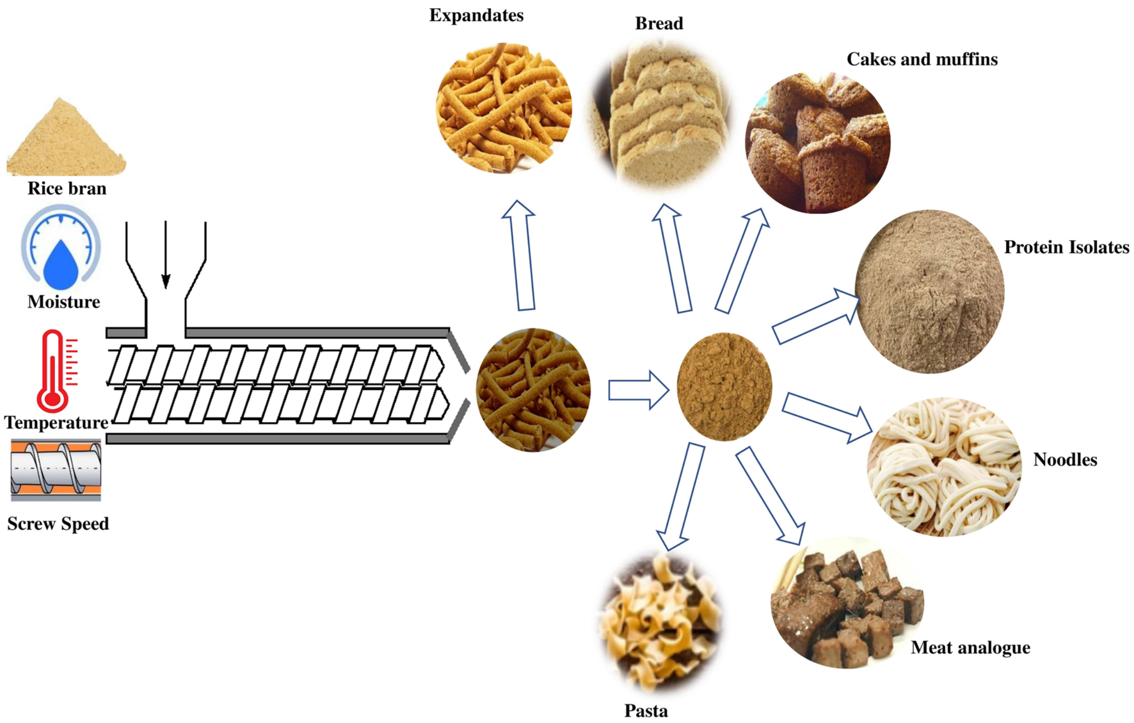

Fig. 2 Extrusion parameters and depicting the use of extruded bran in different foods.

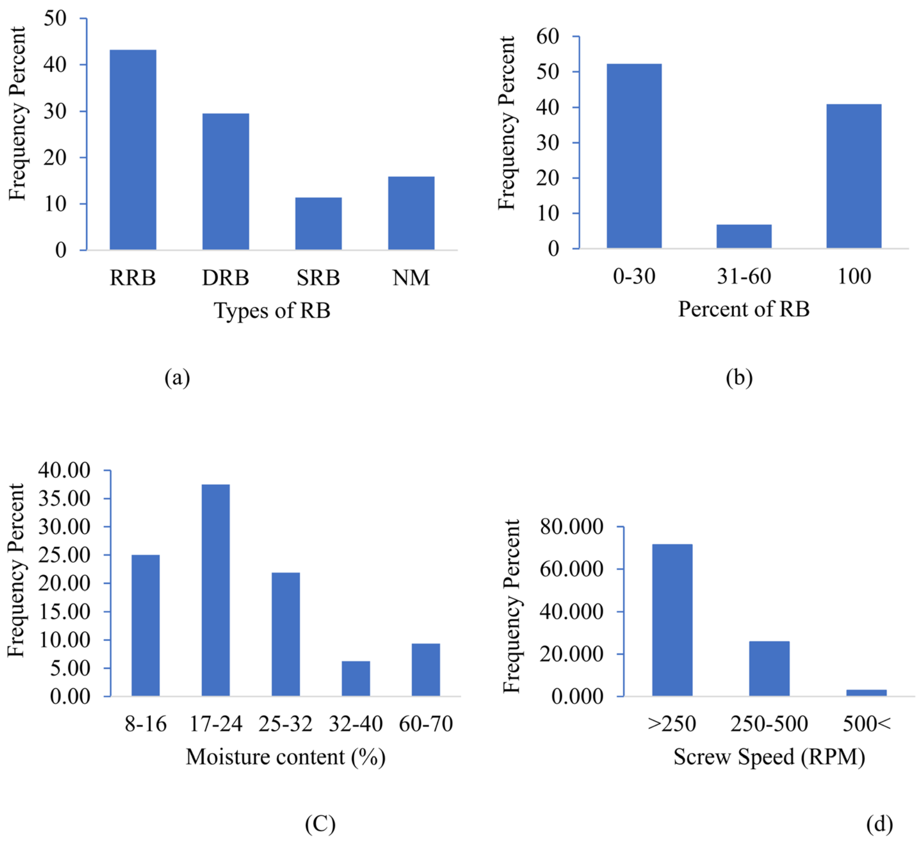

Fig. 3 Frequency of studies depicting (a) types of RB used, (b) percent of RB used, (c) range of moisture used and (d) range of screw speed used.

Table 1 Extrusion of rice bran with other feed mixtures[a]

	Extrusion conditions						
	Feed composition		Screw speed	Temperature	Moisture content		
S. N.	RB (%)	Others	(RPM)	(°C)	(%)	Effect on dependent variables (quality parameters)	References
1	100 (de-oiled and extruded)	0	Compared with full-fat RB, wheat bran and stabilized full-fat extruded RB			(↑)*: water absorption, fat absorption, acid detergent fibre, foaming capacity De-oiled extruded had stable foams	56
2	100 (raw)	0	800	120	9.5–15	An increase in moisture level increased the bulk density	53
3	10, 20, 30 (raw)	Rice flour: 70, 80, 90%	200 and 300	26.7–121.1	—	1. (↓)*: SME, expansion, colour 2. (↑)*: dietary fibre	74
4	100 (raw)	0	225, 305, 450	162.7	—	Phytate (↓)*, copper (↑), calcium, (↓)* zinc (↑)* The effects are based on RPM	75
5	5, 10, 15 (de-oiled)	Semolina (commercial and laboratory bran showed similar results)	130	130	20	1. (↑)*: density, initial viscosity setback viscosity 2. (↓)*: ER, WAI, peak viscosity, gelatinization temperature, colour, texture, taste, OA	39
	5, 10, 15 (raw)					1. (↑)*: Density, gelatinization temperature, setback viscosity 2. (↓)*: ER, WAI, peak viscosity, initial viscosity, colour, texture, taste, OA	
6	100 (raw)	0	225, 305, 450	162.7	—	IF (↓)*, SF (↓), phytate (↑)	62
7	100 (raw)	0	9–250	120–140	—	Changes in nutritional components Vit. B1 (↓)*, Vit. B2 (↓)*, IDF (↑)*, SDF (↓)*	70
8	100 (raw)	0	—	135–140	—	BD (↑)*, WAI (↑)*, WSI (↑)*, far absorption (↓)*, protein solubility (↓)*, damaged starch (↑)*, reducing sugar (↓), non-reducing sugar (↓), total sugar (↓), total fibre (↑)*, lysine (↓)*, phytic acid (↓)*	49
9	4 (raw)	Rice flour 86% + corn starch 8% + 2% potato starch	20.1–32.6	69.8–120.2	26.6–33.4	1. SS: ER (↓)*, BD (↑)*, WAI (↑)*, WSI (↑)*, hardness (↓), adhesive force (↓)*, springiness (↑)*, gumminess (↓)*, cohesiveness (↓) 2. T: ER (↓), BD (↓)*, WAI (↓)*, WSI (↑)*, hardness (↓), adhesive force (↓)*, springiness (↑)*, gumminess (↑)*, cohesiveness (↑)* 3.MC: ER (↓)*, BD (↑), WAI (↑)*, WSI (↓)*, hardness (↓), adhesive force (↑)*, springiness (↓)*, gumminess (↓), cohesiveness (↓)	50
10	9 (NM)	Broken rice 81% + dried soya bean 10%	250	60–110	12–20	1. T: colour (↑)** 2. MC: EI (↓)**, BD (↓)**, colour (↓)**	32
11	10, 15, 20 (de-oiled)	Rice flour (40, 45, 50%) (constant = 20% corn grit, and others	—	130, 140, 150	14, 17, 20	RB: ER (↓)**, BD (↑)**, WAI (↓)**, WSI (↓)**, hardness (↑)**, TDF (↑)**, IDF (↑)**, SDF (↑), TPC (↑)**, AA (↑)** T: ER (↑)**, BD (↓)**, WAI (↑)**, WSI (↑), hardness (↓), TDF (↑), IDF (↑), SDF (↑), TPC (↑), AA (↑) MC: ER (↓)**, BD (↑)**, WAI (↑)**, WSI (↓)**, hardness (↑)**, TDF (↓), IDF (↓), SDF (↓), TPC (↓)**, AA (↓)**	46
12	100 (de-oiled)	0	—	115–165	14–20	Phytic acid (↓)**, polyphenols (↓)**, oxalates (↓)**, trypsin inhibitor (↓)**	34

Table 1 (*Contd.*)

S. N.	Extrusion conditions					Effect on dependent variables (quality parameters)	References
	Feed composition		Screw speed	Temperature	Moisture content		
	RB (%)	Others	(RPM)	(°C)	(%)		
13	100 (raw)	0	200	120	12–17	Total phenolics (↑)**, total anthocyanins (↑)*, total antioxidant activity (↑)*	33
14	10, 20, 30 (de-oiled)	Rice flour	500	25–170	17	(↓)*: DPPH, TPC, (↑)*: moisture, water activity, free fatty acid (the effects are based on the six-month storage period)	76
15	10 (stabilized)	Rice	250	Feed (55 °C), compression metering zones (75 °C), die head (95 °C)	25	1. (↓)*: Peak viscosity, trough, breakdown, final viscosity, set back viscosity, gelatinization enthalpy 2. (↑)*: pasting temperature, thermal properties (onset peak and conclusion temperatures)	37
16	0–45 (extrusion stabilization)	Polished broken rice (55–100%)	200	60–150	20	1. (↓)*: peak viscosity, thermal enthalpy, SDS, TPC, DPPH, ABTs, FRAP 2. (↑)*: WAI, WSI, RDS, RS	48
17	100 (de-oiled)		80–160	80–140	30	SS: Extraction of arabinoxylans (↑)* and molecular weight of arabinoxylans (↓)*	77
18	100 (de-oiled)	0	50 and 100	100	—	Higher water addition and increased SS increased solubility, soluble starch, pentosans, ash and SDF. extrusion-enzyme treatment noticeably increased the SDF, especially the soluble pentosan content	41
19	2–4 (NM)	Corn (92–96%), pigeon pea broken (2–4%)	350	110, 120, 130	15–20	1. Feed : ER (↓)*, BD (↑)*, MF (↓)*, SME (↑)* colour, (↓)*, MR (↑)* (the effects are due to the increase of RB) 2. T: ER (↑)*, BD (↓)*, MF (↑)*, SME (↓)* colour (↑)*, MR (↓)* 3. MC: ER (↑)*, BD (↓)*, MF (↑)*, colour, (↑)*, MR (↓)*, SME (↓)*	47
20	20 (de-oiled)	Rice flour (70%) (constant = 10% corn flour)	116–284	86–154	12–18	1. SS: LE (↑)*, BD (↓), WAI (↓), WSI (↑)*, hardness (↓)* 2. T: LE (↑)*, BD (↓)*, WAI (↓)*, WSI (↑)*, hardness (↓)* 3. MC: LE (↓)*, BD (↑)*, WAI (↑)*, WSI (↓)*, hardness (↑)*	31
21	100 (de-oiled)	—	300	70–134	25	(↑)*: free, bound, and total phenolics, bio accessibility of phenolics, AA	78
22	100 (raw)	—	—	90–110	—	(↑)*: TPC, FRAP, DPPH, and ABTS	79
23	10 and 15 (NM)	Corn grits (90 and 85%)	240	100, 140, 150	16	1. (↓)*: LE, SV, colour, Hc, hardness 2. (↑)*: Crispness., RAG, GI, WRC	45
24	100 (raw)	0	250	100–180	11–23	1. (↑)*: SDF, extraction rate, water solubility, bile salt cholesterol and glucose binding capacity, AA, stretching vibration 2. (↓)*: IDF, TDF, protein, starch, ORC "WRC gradually decreased with the increasing extrusion cooking temperature, gradually increased with the increasing material moisture"	40
25	25, 40, 55 (de-oiled)	Soya protein isolate (75, 60, 45%)	400	130	25	ER (↓)*, BD (↑)*, WAC (↓), WHC (↑), OHC (↓)*, springiness (↓)*, hardness (↓)*, cohesiveness (↓)*	30

Table 1 (*Contd.*)

	Extrusion conditions						
	Feed composition		Screw speed	Temperature	Moisture content		
S. N.	RB (%)	Others	(RPM)	(°C)	(%)	Effect on dependent variables (quality parameters)	References
26	100 (raw)	0	130	120	21	γ-Oryzanol (↓), SDF (↑), TDF (↑), Vit. E (↓), esters (↓), heterocycles (↑), ketones (↓), hydrocarbons (↓), acids (↓), aldehydes (↓), phenols (↓)	58
27	20, 35, 50 (de-oiled)	Soya protein isolate (50, 65, 80%) Rice protein isolate (50, 65, 80%)	400	130	25	ER (↑)*, BD (↓)*, WAC (↓), WHC (↑), OHC (↓)*, springiness (↓)*, hardness (↓)*, cohesiveness (↓)* ER (↑)*, BD (↓)*, WAC (↓), WHC (↑), OHC (↓)*, springiness (↓)*, hardness (↓)*, cohesiveness (↓)* Results seem to be contradictory due to the higher amount of protein in the feed	69
28	100 (raw)	RB in 3 pre-treatments: extrusion hydrolysis (EH-FC), enzymatic extrusion (E-FC) and traditional hydrolysis (H-FC), RPM (50), MC (30–40%), temperature constant (105 °C at zone 5)				Starch: RB > EH-FC > E-FC ≥ H-FC Protein: RB > E-FC > EH-FC ≥ H-FC Ferulic acid: E-FC > EH-FC ≥ H-FC > RB Pentose: H-FC > E-FC > EH-FC ≥ RB Yield of pentose and ferulic acid: E-FC ≥ EH-FC > HFC Note: ≥denotes higher value but not significant while >denotes higher value with a significant difference	59

[a] Note: (↑): increase, (↓): decrease, *: significant, SS: screw speed, T: temperature, MC: moisture content, LE: lateral expansion. ER: expansion ratio, EI: expansion index, BD: bulk density, SV: specific volume, Hc: hydration capacity, WRC: water retention capacity, WAC: water absorption capacity, WHC: water holding capacity, OHC: oil holding capacity, ORC: oil retention capacity, WAI: water absorption index, WSI: water solubility index, GI: glycemic index, RAG: rapidly available glucose, SME: specific mechanical energy, IDF: insoluble dietary fibre, SDF: soluble dietary fibre, IF: insoluble fibre, SF: soluble fibre, TDF: total dietary fibre, DF: dietary fibre OA: overall acceptability, MR: moisture retention, TPC: total phenolic content, AA: antioxidant activity, RDS: rapidly digestible starch, SDS: slowly digestible starch, RS: resistant starch, MF: mass flow rate, DPPH: 2,2-diphenyl-1-picrylhydrazyl, ABTS: 2-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid), FRAP: ferric reducing antioxidant power.

water or other ingredients, forming a dough-like mixture fed into an extruder with a rotating screw in a barrel. The mixture encounters high temperatures and pressure as it moves through the barrel. The mechanical action of the rotating screw facilitates mixing, cooking, and shaping, leading to significant physical, chemical, and structural changes in the raw material.[37–39] These changes encompass starch gelatinization, protein denaturation, cell structure disruption, and modification of fibre content and solubility.[40,41] The impact of process variables on the quality of expanded extrudates incorporating RB and extruded RB is examined in this discussion.

3.1 Rice bran in feed

RB, rice, and corn are prominent carbohydrate sources in the extrusion feed system (Table 1). The interplay of carbohydrates, mainly starch, fibres, and proteins, is important in the extrusion process. Fig. 4 provides the schematic description of the changes in RB protein (RBP), RB starch and fibres that occur while passing through the extruder. RB starch undergoes a phase change from a glassy state to a rubbery state that increases the viscoelasticity of the product, as experienced in the RB-incorporating soya bean protein isolate.[42] Starch, composed of amylose and amylopectin,[43] significantly influences extrudate texture, viscosity, and expansion.[44,45] The expansion ratio (ER) and lateral expansion (LE) quantify extrusion-induced size changes. The water absorption index (WAI) measures absorbed water, while the water solubility index (WSI) quantifies soluble solids from the product. Extrudate hardness correlates with the force required for breakage.[45] Higher starch content (lower RB proportion) increases expansion,[30,39,45–47] WAI,[39,46,48] and WSI,[30,46,48] while reducing bulk density (BD)[30,39,46] and hardness.[27,46] Amylose content in starch influences the texture and cooking quality. Hard texture[27,46] and less expansion is observed when there is more amylose. Smaller starch granular size promotes better extruder flow, favouring RB incorporating feed, despite polyhedral granule (irregular shape) friction requiring higher extrusion pressure than corn starch[45,47] that has round granules and bigger starch size. Optimising the extrusion process (20 rpm, 95 °C die head temperature) to stabilise RB and its addition by 10% in feed brings significant benefits. It reduces viscosity and gelatinization enthalpy, transforms the crystalline structure into a fibrous, porous starch gel, and enhances water-holding capacity with minimal syneresis during storage.[37] This suggests that higher water absorption during extrusion affects gelatinization and viscosity.

Insoluble fibres in the RB do not undergo phase change due to the additional hydrogen bonding and more rigid molecular structure. However, shear and heat during the extrusion result in fragmented fibres (Fig. 4). The presence of soluble fibres increases the solubility during extrusion, which can be attributed to the change in the microstructures of the fibres.[41] Scanning electron micrographs (Fig. 5) depict that the honeycomb-like cell wall structures were disrupted after extrusion cooking, indicating a dissociation of the complex matrix.[41]

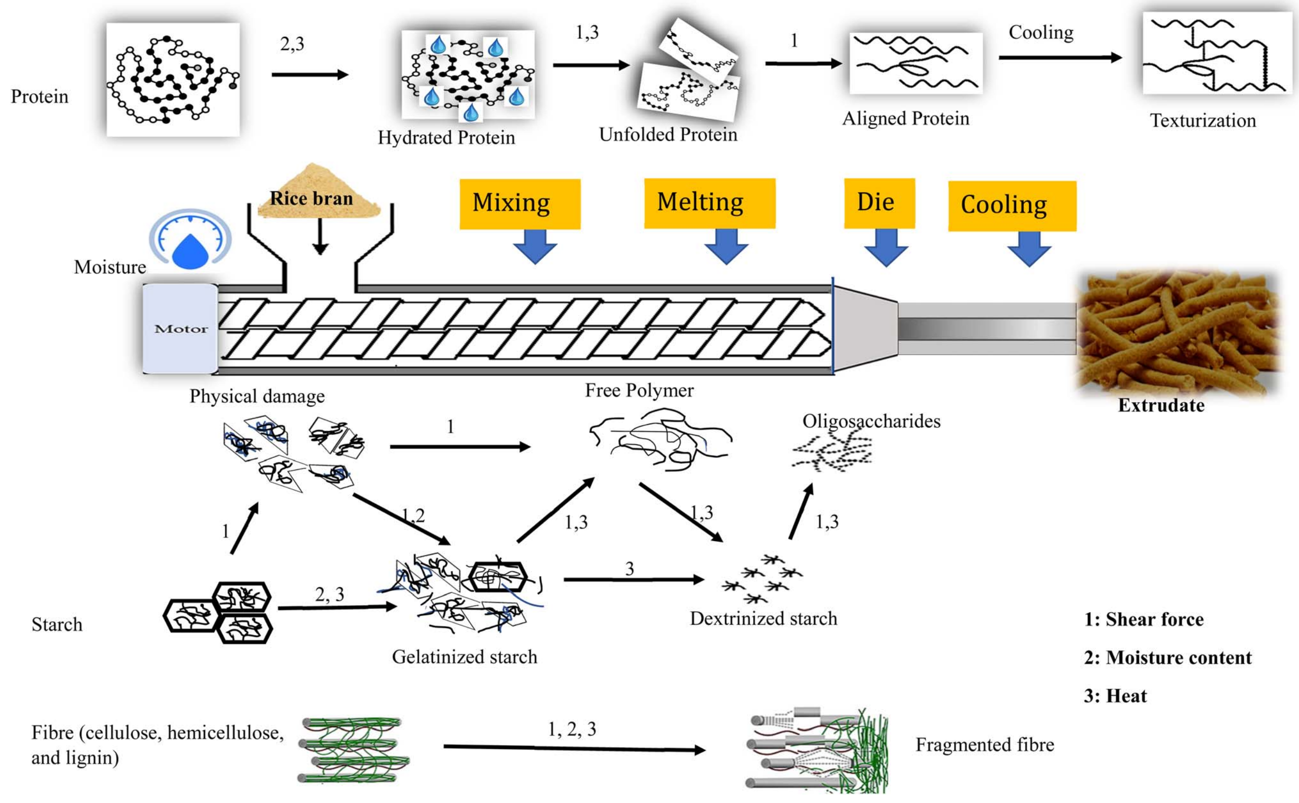

Fig. 4 Schematic description of the changes of RBP, RB starch, and fibres in the extruder.

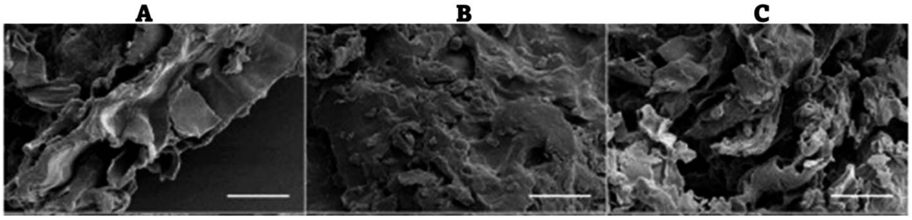

Fig. 5 Scanning electron micrographs (SEM) of rice brans (A) extruded, (B) simultaneously extruded & xylanase treated and (C) sequentially extruded & xylanase treated.

Incorporating 10–20% RB boosts insoluble fibre and lowers starch content in the composite flour containing rice flour and corn grit, reducing WAI and WSI.[46] This might be due to the entrapment of water molecules by the fibres, which prevents them from being released. In semolina-based composite feed with 5%, 10% and 15% RB, similar WAI results were found,[39] which increased expansion and reduced bulk density. Adding RB was also noted to elevate bulk density and decrease the lateral expansion.[39,46] This is due to water molecules being trapped by fibres, limiting free water for lateral expansion, and the increased fibre presence acting as a barrier that reduces lateral expansion and increases bulk density.

RBP is disrupted and amino acid chains joined by peptide bonds unfold because of temperature and moisture changes during extrusion. The melted protein is texturized into a fibrous structure by orienting the cross-linked peptide chains in a specific direction within the cooling die (Fig. 4). Replacing soy protein isolate (SPI) with 25%, 40%, and 55% DRB significantly altered the texturized soy protein product (TSP) properties. This reduced bulk density, water absorption capacity (WAC), oil holding capacity (OHC), hardness, springiness, and cohesiveness.[30] DRB contains only 17.59% protein compared to SPI's 84.40%. This protein disparity is crucial because protein influences food product structure and density. Replacing SPI with DRB naturally reduces bulk density.

Proteins have hydrophilic and hydrophobic properties that affect water and oil absorption capacities. The lower protein content in DRB likely contributes to reduced water and oil absorption. Additionally, it may weaken protein–protein interactions in DRB-containing samples, and the TSP extrusion process (400 rpm and 130 °C) could further alter the amino acid composition. These alterations in amino acid composition can impact protein–protein interactions and subsequently affect the texture of the TSP. Adding soluble dietary fibre (SDF) and insoluble dietary fibre (IDF) extracted from extruded RB at 0%, 4%, 8%, 16% and 20% reduced maximum hardness and positive peak work area. This presence of dietary fibre in the rice starch system weakened gel strength and effectively prevented rice starch retrogradation compared to unextruded samples, likely due to structural changes induced by extrusion cooking.[38] Incorporating 10% and 15% RB into corn grit during extrusion increased water retention capacity (WRC) but decreased hydration capacity.[45] This is attributed to reduced starch availability leading to increased crispness but lower specific volume, hardness, and lateral expansion. These findings underscore the diverse impact of starch and fibre properties on the extrusion process. Supplementing with RB altered the rheological properties of extrudate dispersions and resulted in a decreased predicted glycaemic response for RB-enriched snacks. This effect may be attributed to the modulation of starch digestion.[45] Whole RB, when extruded at 135–140 °C for stabilization, displays enhanced bulk density, WAI, and WSI.[49] These improvements can be attributed to starch solubilization and fibre-related changes.

Extruded product functionality, impacted by viscosity, retrogradation and thermal properties, has been studied by many researchers.[37–39] Substituting semolina with 5%, 10% and 15% RB[39] and incorporating 10% stabilized RB into the feed as reported by Wang *et al.*[37] led to decreased viscosity parameters (peak viscosity, trough viscosity, breakdown viscosity, final viscosity, setback viscosity and gelatinization temperature) while increasing pasting temperature and thermal properties. Lower peak viscosity reveals the lower swelling capacity of the starch. Adding 0–45% RB in polished broken rice decreased the viscosity, and the reason is reduced starch availability.[48] Breakdown viscosity refers to the reduction in viscosity or resistance of a starch paste or gel under applied shear or heat. Setback viscosity measures the extent of retrogradation and represents the ability of the starch gel to regain its viscosity or firmness after cooling. RB hinders amylopectin, reducing water absorption and breakdown viscosity.[37,48] Reduced setback velocity signifies less retrogradation tendency. Incorporating RB into the fibrous and porous structure reduces the retrogradation rate and viscosity. Adding RB in the feed system decreases retrogradation endothermic transition temperatures and melting enthalpies for the retrograded sample due to the inhibition of amylopectin crystallite formation, as supported by the studies of Wang *et al.* and Wu *et al.*[38,39] Fibrous RB fragments (soluble and insoluble dietary fibres) disrupt starch film, affecting bubble formation and water absorption during extrusion. Extrudate fibre addition at 4%, 8%, 16% and 20% increases gelatinisation temperature and reduces setback and breakdown viscosities. RB-derived dietary fibre effectively counters long-term starch staling.[38]

In conclusion, RB incorporation alters the extrudate characteristics, impacting expansion, viscosity, and retrogradation. Interaction between starch and fibre and their properties modulate extrusion outcomes and contribute to the product's functional attributes.

3.2 Effect of temperature on RB incorporating feed

Temperature plays a significant role in the extrusion process. Adjusting and optimising the barrel and die temperatures are essential to achieve the desired rheological properties, expansion, and textural characteristics of the extruded product. Producers can control parameters such as melt viscosity, starch gelatinization, and expansion rate by manipulating the temperature during extrusion to attain the desired attributes in extruded products. Incorporating 4% RB into a composite of 86% rice flour, 8% corn starch and 2% potato starch between 69.8 and 120.2 °C decreased expansion, BD, WAI, hardness, and adhesive force but increased WSI and textural parameters (springiness, gumminess, and cohesiveness).[50]

In the 60 to 110 °C temperature range, a composite feed with 9% RB, 81% broken rice, and 10% dried soybean saw an increase in colour intensity.[32] At higher temperatures (130 °C, 140 °C and 150 °C), extruding a composite feed containing 10–20% defatted RB in rice and corn resulted in higher levels of phenolics, antioxidants and dietary fibres.[46] For pigeon pea and corn composites with 2–4% RB, extrusion temperatures of 110 °C, 120 °C and 130 °C increased the expansion and colour values.[47] Extrusion temperatures of 86 to 154 °C were utilised for rice and corn flour composite with 20% DRB.[31] An increase in temperature leads to enhanced expansion,[31,46,47] WSI,[31,50] colour,[32,47] and WAI[46] of the expanded extrudates. Conversely, as the temperature rises, the bulk density decreases[31,46,47,50] alongside hardness.[46,50] Compared to previous studies, some contradictory results have been observed, where an increase in temperature led to reduced expansion,[50] WAI[31,50] and WSI.[46] This discrepancy might be attributed to variations in gelatinization and viscosity of the feed caused by temperature fluctuations. The degree of water superheating increases with rising temperature, resulting in more expanded products.[31] Superheated water evaporates upon leaving the die, contributing to a reduction in bulk density. Higher temperature within the barrel and lower feed moisture might lead to reduced pressure and, consequently, less expansion.[50] In most studies, the temperature range falls between 100 and 180 °C, where starch gelatinises and dextrinizes, proteins denature, and fibres fragment. At elevated temperatures, the residence time of the melt in the extruder decreases, minimising feed exposure[51] and potentially enhancing the brightness of the extrudates. Extrusion cooking at higher temperatures will affect the RB component in the feed. The extrusion can increase the content of soluble dietary fibres (SDF) while decreasing the content of insoluble dietary fibres (IDF) and total dietary fibre (TDF). This implies that high-temperature extrusion can break down glycosidic bonds between RB fibre molecules, converting larger-molecule IDF into smaller-molecule SDF. This highlights how extrusion can enhance the solubility and availability of dietary fibre.[40] At 100 °C and 120 °C extrusion temperatures, whole RB's soluble dietary fibre (SDF) showed enhanced ABTS and DPPH scavenging, bile salt, cholesterol, and glucose binding capacities. This improvement resulted from increased viscosity, porosity, and surface area. Above 140 °C, water solubility and retention capacity increased as complex structures broke down, lowering molecular weight and particle size. However, temperatures exceeding 120 °C reduced binding properties and oil retention.[40] During 100% DRB extrusion at 140 °C, there was a significant reduction in phytic acid, polyphenols, oxalates, and trypsin inhibitors. Higher temperatures reduced these antinutritional components more effectively by denaturing or breaking them down, making them less bioavailable or easier to remove.[34]

3.3 Effect of screw speed on RB incorporating feed

In the extrusion process, the screw speed is pivotal in determining the rate at which the material is pushed forward. This factor significantly influences the feed's shear force and melt temperature, impacting the expansion reduction and bulk density increase. Notably, when incorporating 4% RB in a mixture of 86% rice, 8% corn, and 2% potato, operating within 20 to 32.6 rpm yielded comparable outcomes as indicated by Liu *et al.*[50] However, altering the feed composition to substitute 20% rice flour with RB while operating the extruder at speeds ranging from 116 to 284 rpm resulted in contrasting effects. This discrepancy can be attributed to the distinct characteristics of the feed that includes 20% DRB in 70% rice flour and 10% corn flour, as observed in the study by Sharma *et al.*[31] Increasing the screw speed intensifies ingredient mixing and shearing, leading to improved starch dispersion and gelatinization, ultimately resulting in enhanced expansion. An increase in screw speed correlates with elevated values for WAI in 4% RB incorporating feed,[50] as well as WSI,[31,50] along with enhanced springiness.[50]

Conversely, lower screw speeds lead to prolonged residence times of the RB in the extruder, facilitating higher gelatinization temperatures and an extended timeframe for RB protein denaturation. Conversely, higher speeds induce heightened shear force and greater heat generation within the extruder, thereby causing the unfolding and rearrangement of the RB protein's secondary, tertiary, and quaternary structures. This phenomenon prompts denatured proteins of RB to exhibit a higher tendency to interact, forming aggregates. Consequently, such alterations of RB influence textural properties, reducing hardness, cohesiveness, and gumminess.[50] In the context of meat analogues containing 15% RB in soya protein isolates, increasing the screw speed yields noteworthy effects. It reduces hardness as RB spends less time in the extruder barrel, leading to decreased molten protein aggregation and sulfhydryl group transformation. Adhesiveness and chewiness also decline with higher screw speeds, while tensile force initially rises before peaking at 280 rpm, which is attributed to the formation of a dense RB fibre network structure at the die due to the dispersion of the dispersed phase in the continuous phase.[25] Moreover, higher speeds cause RB fibres to fragment into smaller segments, altering their alignment and reducing hardness. This trend is evident across various studies incorporating 4 to 20% RB in different feed systems.[25,31,50]

3.4 Effect of moisture content on RB incorporating feed

Moisture plays a critical role as a plasticizer, reducing material viscosity and facilitating smooth flow through the extruder. This characteristic contributes to effective material mixing and lubrication. Furthermore, moisture aids in controlling extruder heat and vaporises upon passage through the die, influencing texture and physical properties. RB inclusions increase fibre content, encouraging enhanced water absorption capacity due to greater fibre–water interaction.[31,46,50] However, WSI decreases within the moisture content range of 12 to 33.4% due to increased fibre content. The fibre acts as a physical barrier to water, restricting interaction between the fibre and matrix and thus reducing WSI, consistent with the findings of different researchers.[31,46,50] Adequate moisture is essential for steam generation during extrusion, a process crucial for expansion. Although it may appear intuitive that moisture promotes expansion and reduces bulk density in composite flour consisting of 2–4% RB added in 92–96% corn, and 2–4% pigeon pea broken, with a moisture content of 15–20%,[47] contradictory findings have also been reported.[31,46,50] Increased fibre incorporation exacerbates moisture entrapment, hindering gas escape through the die. This phenomenon likely contributes to reduced expansion in RB-enriched extrudates. The addition of 20% DRB to a feed mixture of 70% rice flour and 10% corn flour, with moisture ranging from 12–18%,[31] as well as 15–20% RB inclusion in rice and 14–20% moisture,[46] both led to increased extrudate hardness linked to reduced expansion. Conversely, a feed containing 4% RB added to a composite of rice, corn, and potato starch, with based moisture levels between 26.6 and 33.4%, showed no significant reduction in hardness, gumminess, or cohesiveness but exhibited increased adhesive force and decreased springiness.[50] Higher moisture levels promoted better adhesion between the fibre and matrix, enhancing product elasticity and springiness. Moisture levels during extrusion impact antinutritional components in RB. Higher moisture (14–20%) in feed with 100% DRB aids in the breaking down of phytic acids, oxalates, and trypsin inhibitors by hydrating and softening the RB.[34] In contrast, 20% DRB feed with 12–18% moisture showed reduced expansion, increased bulk density, and greater hardness.[31] These changes may be due to altered pressure, potential energy, RB starch structure, and degradation driven by moisture. Similar effects on expansion and bulk density were observed in RB-containing extrudates.[32,46,50] However, higher moisture levels increased expansion, mass flow rate, and reduced bulk density and specific mechanical energy in corn-based feed composites with 2–4% RB and 2–4% pigeon pea.[47] This is attributed to the inclusion of high-fibre and high-protein components, enhancing plasticity, and reducing dough elasticity, enabling more significant expansion during extrusion.

In conclusion, moisture has a multifaceted impact on the properties of materials containing RB during extrusion, affecting viscosity, material flow, lubrication, heat control, water absorption, expansion, and product characteristics. Moisture content and the addition of RB in the feed cause changes in pressure, potential energy, and feed plasticization in the extruder. The molecular structure of RB starch and protein also contributes to extrudate properties. The complex interaction between moisture content, fibre and protein incorporation, and resultant outcomes underscores the need for careful consideration in extrusion processes.

4. Effect of incorporation of defatted and stabilized rice bran

In the context of extrusion, RB can be used in various forms: either raw defatted (de-oiled) or stabilized. This review examines the impact of these different forms of RB on the extrusion process and the resulting quality of the extrudates. The forms of RB used in the extrusion process are detailed in Tables 1 and 2. Defatting RB significantly impacts its composition and functional properties. Hexane in the Soxhlet apparatus was used for defatting RB.[34,39] While most articles (Tables 1 and 2) do not mention defatting methods, various extraction methods, including microwave-assisted, ultrasound-assisted, supercritical CO_2, subcritical CO_2, subcritical water, and Soxhlet extraction are discussed by Punia *et al.*[52] The defatted RB can induce changes in the extrusion process and the characteristics of the final extrudates. Notably, defatting has been shown to enhance the expansion and texture of extrudates. For instance, in a study by Sekhon *et al.*,[39] the extrusion results demonstrated that the addition of the 15% defatted RB in wheat semolina improved the ER, BD, and WAI, yielding values of 1.22, 0.45 g cm^{-3} and 2.17%, respectively, compared to 1.96, 0.4 g cm^{-3}, and 4.35% for the full-fat RB counterpart. Additionally, colour and texture assessments (sensory scale 1–9) indicated notable improvements with 15% defatted RB than full-fat RB samples with values of 7.0 & 7.8 and 2.3 & 2.7, respectively.[39] The defatting process leads to a reduction in fat content and an increase in crude fibre content, which in turn, raises the shear force during extrusion. This increased shear force can also be attributed to decreased dough mass temperature due to increased bran fibre. Ultimately, the increased pressure within the die contributes to enhanced expansion and a lighter texture in the extrudates. Moreover, the absence of fats from defatting diminishes the lubricating effect during extrusion, increasing friction and shear forces, and further promoting improved expansion and texture.

However, it is crucial to acknowledge that the lipids may result in oxidation, leading to product discolouration, yellowing, and browning. This oxidative process is more noticeable in products from non-defatted RB, such as extrudates[32,39,47] and soya protein isolates.[25] Although defatting offers benefits, it is worth noting that it also leads to a reduction in antioxidants and micronutrients such as tocopherols, tocotrienols, β-sitosterol, and phytosterols ferulic acid and γ-oryzanol.[52]

Stabilization is a critical step involving the deactivation of the lipase enzyme in RB. When rice starch was enriched with 10% extrusion-stabilized RB and extruded at 250 rpm with 25% moisture, there was a significant decrease in viscosity and gelatinization enthalpy compared to the untreated starch. The extruded starch with stabilized RB exhibited a fibrous, porous structure, higher water-holding capacity, and less syneresis during storage. Furthermore, the addition of stabilized RB delayed starch retrogradation (the realignment of starch

Table 2 Extruded brans in different food systems[a]

	Feed composition					
S. N.	RB (%)	Others (%)	Extrusion conditions	Product	Quality parameters	References
1	3, 6, 9% (raw)	Wheat flour	Extrusion temperature 115 °C	Bread	Improvement in fermentation capacity and gas retention capacity of dough The specific total volume of bread (↑)*, sensory quality of bread (↓)*	28
2	100 (de-oiled)		(Twin-screw extruder) the RB blends were extruded at four different die-exit temperatures: 100, 120, 140, or 160 °C, MC (20%)	RB protein	Peak of the denaturation curve (↑)*, enthalpy the denaturation (↓)*, unordered structure (↑)*, α helix (↑)*, β sheet (↓)*, β turn (↓)*, Trp band (↓)*, Tyr doublet (↓), CH band (↓)*	68
3	5–25% (RB fibre)	Rice flour	Moisture (30%), RPM (100), temperature (50–100 °C)	Pasta	(↑)*: TDF, IDF, SDF, WSI, and cooking loss (↓)*: WAI, colour, chewiness, hardness, and crystallinity	80
4	100 (NM)	Rice flour (RB : rice flour: 1 : 9)	(Twin-screw extruder) moisture content, extrusion temperature, and screw speed were 11%, 120 °C, and 250 rpm, respectively	Noodles	TPC (↑)*, DPPH (↑)*, ABTS (↑)*, starch digestibility (↓)*, RDS (↓)*, SDS (↓), RS (↑)*, pGI (↓)*, HI (↓)*, water absorption rate (↑)*, cooking loss (↑), cooking time (↓)*, hardness (↑)*, shearing work (↓)*, stickiness (↑)*, tensile strength (↓)*, elasticity (↓)	27
5	3–12% (RBIDF)	Rice flour (note: RBIDF was obtained by (*Amyloglucosidase*)	RPM (100) (twin-screw extruder) The temperatures in parts 1 to 4 of the screw were 70 °C, 90 °C, 105 °C, and 92.5 °C	Noodles	Cooking loss (↑)*, hardness (↓)*, chewiness (↓)*, crystallinity (↓)*, starch hydrolysis (↓)*, OA (↓)* (sensory and structural properties vary with RB concentration)	81
6	100 (raw)	RB: white rice flour = 1 : 8	(Twin-screw extruder) temperature (90–160 °C), RPM (150), MC (18–40%)	Rice cake	SC (↑)*, WHC (↑)*, WSI (↓)*, TPC (↑)*, IDF (↓)*, SDF (↑)*, TDF (↓), γ-oryzanol (↑)*, GABA (↑)*, break down viscosity (↑)*, peak viscosity (↑)*, trough viscosity (↑)*, setback (↓)*, gelatinization enthalpy (↓)*: (in the extrudate), hardness (↓)*, springiness (↑)*, adhesiveness (↓)*, chewiness (↓)*, cohesiveness (↑)*, resilience (↑)*, specific volume (↑)*: (in the cake)	26
7	100 (de-oiled)		MC (20%), RPM (20), temperature gradient started at 48 °C, with a gradual increase up to 120 °C; leaving at 150 °C	Protein concentrate	Oil absorption capacity (↑)*, emulsion activity index (↑)*, emulsion stability index (↓)*, foam capacity (↑)*	55
8	100 (raw)	4%, 8%, 16% and 20% in rice starch	RPM (250), temperature (160 °C) and MC (11%)	Rice starch	1. (↑)*: onset temperature, transition temperature, pasting temperature 2. (↓)*: gelatinization enthalpy, positive peak area, hardness	38
9	5, 10, 15, 20 (stabilised bran)	Soya bean protein isolate	(Twin screw extruder) RPM (280), constant temperature in different zones (60–150 °C), MC (70%)	Plant-based meat	Hardness, adhesiveness, chewiness (first increased then decreased and maximum at 10% RB), elasticity (↑)*, HB (↑)*, HI (↑)*, DB (↑)*, and HB + DB (↑)*, stretching vibration (↑)*	42
10	(Raw)	SPI : RB = 17 : 3	Temperature of the cooking zone (130–170), RPM (240–320), MC (64–72%)	Meat analogue	1. MC: hardness (↓)*, elasticity (↓)*, adhesiveness (↓)*, chewiness (↓)*, L (↑)*, a (↓)*, b (↑)*, colour difference (↓)*, transverse tensile force (↓)*, longitudinal tensile force (↓)*, α helix (↑)*, β1 (↓)*, β2 (↓)*, β sheet (↓)*, β turn (↑), random (↓)* 2. Temperature: hardness (↑)*, elasticity (↓)*, adhesiveness (↑)*,	25

Table 2 (*Contd.*)

	Feed composition					
S. N.	RB (%)	Others (%)	Extrusion conditions	Product	Quality parameters	References
					chewiness (↑)*, L (↓)*, a (↑)*, b (↓)*, colour difference (↑)*, transverse tensile force (↑)*, longitudinal tensile force (↑)*, α helix (↓)*, β1 (↑)*, β2 (↑)*, β sheet (↓)*, β turn (↓)*, random (↓)* 3. Screw speed: hardness (↓)*, elasticity (↓)*, adhesiveness (↓)*, chewiness (↓)*, colour difference (↑)*, transverse tensile force (↑)*, longitudinal tensile force (↑)*, α helix (↑)*, β1 (↓)*, β2 (↓)*, β sheet (↓)*, random (↑)*	
11	100 (raw)		(Twin-screw extruder) temperature (110 °C), MC (8%)	Powder	Effect of micronization: whiteness (↑)*, WSI (↑)*, nutrient release (↑)*, particle size (↓)*, WBC (↓)*, swelling capacity (↓)*	57
12	8 (NM)	Rice flour	(Twin-screw extruder) MC (11%), RPM (250), temperatures of Zones I, II, III, and IV in the extruder barrel were 60 °C, 90 °C, 120 °C, and 160 °C	Noodles	pH (↑)*, hardness (↑)*, iodine blue value (↑)*, cooking loss (↑)* and starch retrogradation (↓)*	66
13	100 (raw)	0%, 5%, 10%, 15%, and 20% RB added to soya protein isolate	(Twin-screw extruder) temperatures from the first to the fifth temperature zone were (60–150 °C), RPM (280), MC (70%)	Plant-based meat	Network structure (↓) when the RB (5%) (↑), TPC (↑)*, DPPH (↑)*, ABTS (↑)*, FRAP (↑)*	64
14	100 (NM)	9% RB added to rice flour	(Twin-screw extruder) temperatures from the first to the fifth temperature zone were 60 °C, 120 °C, 150 °C, 170 °C, and 180 °C, respectively, RPM (200)	Noodles	(↓)*, 2-hexenal, (*E*)-2-hexenal, heptanal, 2-heptanone, 1-hexanol, octanal, (*E*)-2-heptenal, 2-octanone, and 2-octenal	67
15	100 (NM)	9% RB added to rice flour	(Twin-screw extruder) temperatures from the first to the fifth temperature zone were 60 °C, 120 °C, 150 °C, 170 °C, and 180 °C, respectively, RPM (200)	Noodles	Hardness (↑)*, chewiness (↑)*, and gumminess (↑)*, compact structure (↑)*, [peak viscosity (↓)*, trough (↓)*, set back (↓)*, final viscosity (↓)*, breakdown viscosity (↓)*, pasting temperature (↓)*]: compared to non-extruded bran	44

[a] Note: (↑): increase, (↓): decrease, *: significant, WHC: water holding capacity, SC: swelling capacity, WSI: water solubility index, pGI: predicted glycemic index, OA: overall acceptability, RDS: rapidly digestible starch, SDS: slowly digestible starch, RS: resistant starch, HI: hydrolysis index, GABA: γ-aminobutyric acid, HB: hydrogen bonds, HI: hydrophobic bonds, DB: disulfide bonds, RBIDF: rice bran insoluble dietary fibre, DPPH: 2,2-diphenyl-1-picrylhydrazyl, ABTS: 2-azinobis (3-ethyl-benzothiazoline-6-sulfonic acid), FRAP: ferric reducing antioxidant power.

molecules and gel formation). This delay in retrogradation can enhance the texture and extend the shelf life of extrudates.[37] Stabilized RB also emerges as an excellent source of antioxidants, contributing to increased antioxidant activity. Incorporating 0–45% stabilized RB into rice flour-based extrudates increases free, bound, and total phenolic content levels, which possess antioxidant properties. This is evidenced by the results of 2,2-diphenyl-1-picrylhydrazyl (DPPH), 2-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), and ferric reducing antioxidant power (FRAP) assays. However, it's worth noting that the values of these assays significantly decreased with rising extrusion temperatures. This stabilisation process maintains product quality and improves colour, reduces lipid oxidation and enhances sensory attributes.[48]

In contrast to the existing research, which lacks comparisons under similar extrusion conditions, our review considers the potential effects of the stabilisation process on extrudate characteristics. The process of stabilisation preserves the nutritional quality by preventing the degradation of bioactive compounds and maintaining the integrity of essential nutrients such as protein, lipids, fibres, vitamins, and minerals. It also positively influences the extrusion process and the quality of the resulting product. By effectively elucidating the roles of defatting and stabilisation in the extrusion of RB, this study enhances our understanding of how these processes can influence the final characteristics of extruded products.

5. Effect of extrusion on the physical and nutritional qualities

Extrusion stabilizes the RB, and the food products developed by its addition have improved functional and nutritional properties. Extrusion stands out as an efficient process for inactivating the lipase enzyme and enhancing the physico-chemical properties of RB. A critical temperature threshold for lipase inactivation is noted at 128 °C, while increased moisture levels contribute to increased bulk density of the extrudate.[53] The presence of RB lipids significantly influences the extrusion process, lubricating it and aiding heat transfer for efficient cooking. These lipids also contribute to expansion, a brittle texture, and improved product mouthfeel.[54]

The extrusion of RB at higher temperatures (135–140 °C) results in a darker extrudate colour due to starch breakdown, Maillard reaction and pigment oxidation. This high temperature and high shear yield higher bulk density, water solubility, fat absorption and water absorption indicative of increased starch damage during extrusion.[49] Moreover, a protein concentrate derived from extruded DRB exhibits elevated oil absorption capacity, emulsifying activity index and foaming capacity compared to enzymatic hydrolysis.[55] The increased pressure during extrusion alters protein arrangement, enhancing water absorption capacity and foaming potential.[56] When comparing different extrusion treatments, extruded RB followed by micronization shows superior WSI, whiteness, nutrient release and decreased WBC and swelling capacity compared to radio frequency-treated RB followed by micronization.[57] Total dietary fibre increases due to extrusion,[49,58] likely due to fibre structure breakdown that increases accessibility. Total dietary fibre content variations have been reported due to different extrusion conditions and fibre solubility.[58] During storage, 176 volatile compounds were detected in extruded RB, including esters, heterocycles, hydrocarbons, aldehydes, ketones, acids, alcohols, ethers, and phenols.[58] Similarly, Rashid *et al.*[58] observed reduced vitamin E content and changed volatile substances due to extrusion, leading to aldehydes and ketones that may cause rancidity.

Nevertheless, extrusion proved more effective at stabilizing volatile compounds than dry-heat treatment. Incorporating 4 to 20% extruded RB as soluble and insoluble dietary fibre in rice resulted in a decrease in viscosity (2177 to 1196 cP for soluble dietary fibre and 2178 to 1165 cP for insoluble dietary fibre) and reduced retrogradation, suppressing long-term staling of rice.[38] Additionally, extrusion damaged cell walls, making xylanase more available for arabinoxylan and increasing fermentable oligosaccharides (FOs) yield, thereby saving time in starch and protein removal.[59] Arabinoxylan may function by decreasing the quantity of sugar and cholesterol absorbed in the intestines and stomach. It may also alter the composition of the gut bacteria.[60]

The functional properties of soluble dietary fibre (SDF) demonstrate a relationship with extrusion cooking parameters, with moderate temperatures and moisture content showing enhanced *in vitro* binding capacities and antioxidant activities.[40] Extrusion modifies protein structures and causes the breakdown of complex sugars, potentially leading to Maillard reactions. Protein can be denatured in extrusion due to high temperature and shear force, but many studies suggest no significant effect on the protein content of RB.[61]

Extrusion-induced hydrolysis of phytates in RB contributes to increased mineral availability, such as copper and zinc.[62] In the extrusion of RB, SDF was 51.49% as compared to unprocessed SDF. Additionally, there was an increase in the number of porous microstructures along with a decrease in molecular weight. Higher glucose content and improved antioxidant activities were observed in the extruded RB SDFs.[63] An increase in the DPPH, ABTS, and FRAP suggests the antioxidant activity is due to RB.[64] These are attributed to the presence of bioactive compounds like anthocyanins, flavones and flavanols, ferulic and *p*-coumaric acid, apigenin and quercetin, phytic acids, alpha-tocopherol, ?-oryzanol and phytosterols which have numerous health benefits (Fig. 6). Minerals and phytochemicals have been shown to strengthen immunity and prevent cancer.[65] Dietary fibre consumption is inversely correlated with the risk of colorectal cancer. Tocotrienol inhibits the formation of tumours and lowers the inflammatory environment in the pancreas.[52]

In summary, RB extrusion impacts the resulting products' physical attributes and nutritional content. However, variations arise based on different extrusion conditions and compositional factors.

6. Application of the extruded RB in different food products

RB is a versatile ingredient due to its favourable nutritional profile and functional properties, making it suitable for diverse food applications. The extrusion process enhances its technological properties and reduces antinutritional factors like phytates, broadening its potential uses. Extruded RB finds its application in the preparation of noodles, contributing to improved product quality and enhanced antioxidant activities.[44,66] Significant improvements in antioxidant activity were noted in a study comparing brown rice noodles incorporating extruded RB to white rice noodles and brown rice noodles with un-extruded RB.[27] Extruded RB-incorporating brown rice noodles exhibited reduced contents of rapidly digestible starch (RDS), hydrolysis index, predicted glycaemic index and higher resistant starch (RS). These outcomes were attributed to enhanced phenolic content, DPPH, ABTS scavenging activities and total dietary fibre. Extruded RB contributed to higher resistant starch (RS) content in brown rice noodles, possibly due to dietary fibre enclosing starch granules if DRB was used. However, there is no mention of the types of bran used. So, high-temperature cooking of starch (from rice) and fats and oil (from RB) can be attributed to higher RS. Extruded RB also influences the cooking properties of noodles, reducing cooking time, cooking loss, water absorption, and shear work while

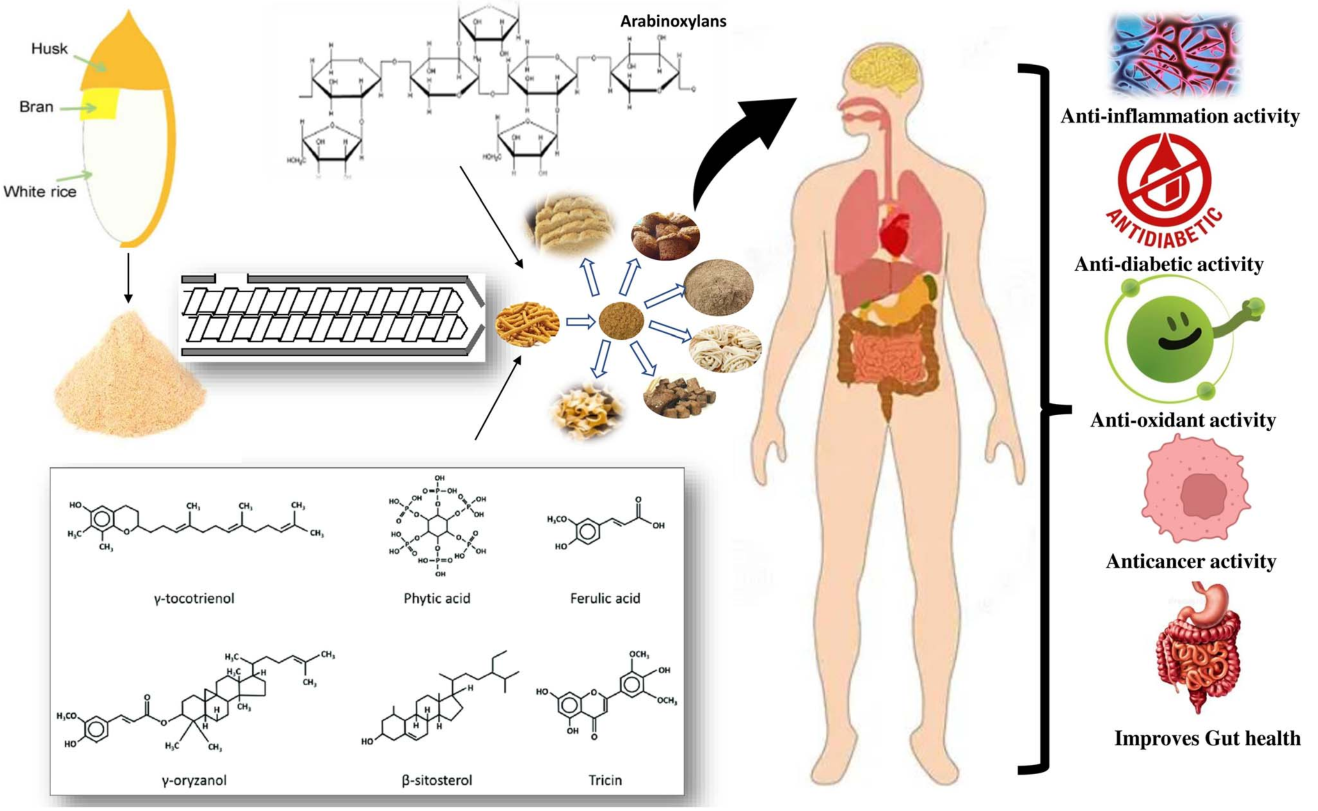

Fig. 6 Potential health benefits of products from RB extrusion.

enhancing hardness, tensile strength, elasticity and stickiness.[27] Noodles with 9% extruded RB had a compact texture and improved cooking stability, chewiness, and gumminess.[44] Similarly, the extrusion of RB reduced the concentrations of 2-hexenal, (*E*)-2-hexenal, heptanal, 2-heptanone, 1-hexanol, octanal, (*E*)-2-heptenal, 2-octanone, and 2-octenal in noodles concluding the influences in the volatile flavour compounds leading to changes in their composition.[67]

Extruded RB delayed the decrease of pH values of the fresh brown rice noodles, reduced the iodine blue value and cooking loss rate, and increased free and weakly bound water during storage, resulting in a regular porous microstructure and better texture and overall eating quality. Extruded RB delayed starch retrogradation at 4 °C.[66] In cake preparation, mixing extrusion-modified RB with semi-dry ground rice flour (1 : 8 ratio) improved cake texture, specific volume, springiness, and resilience compared to traditional brown rice flour. It also enhanced its nutritional value, making it a promising ingredient for improving brown rice products.[26]

Extruded RB was added to soybean protein isolate (SPI) at varying levels (0%, 5%, 10%, 15%, and 20%) to create plant-based simulated meat. The hardness at 10% RB addition was 4267 g, which was 106.23% more than SPI. Similarly, the transverse tensile force increased by 50.37%, and the longitudinal tensile force increased by 64.78%. The enthalpy ΔH (J g^{-1}) value decreased from 32.0 (for 5% RB addition) to 30.5% (for 20% RB addition).[42] The RB addition weakened bonds, increasing the interactions among hydrogen, hydrophobic, and disulphide bonds, leading to increased hardness and decreased thermal stability. It also affected gel network structure and cross-linking force, suggesting potential use in plant-based meat production.[42] Extruded RB also influenced apparent properties like hardness and tensile force due to its interaction with soya protein isolate[25] as discussed earlier. Protein concentrates obtained after extrusion of DRB improved functionality, making them suitable for food formulations.[55] Raman spectroscopy showed an increase in unordered structure and a decrease in the α-helix and β-sheet structures of RBP during extrusion, depending on the extrusion temperature. This influenced tyrosine and tryptophan content and protein polarity.[68] In a study of extrusion followed by micronization,[57] the release of nutrients (phenolics, flavonoids, γ-oryzanol, and minerals) from RB increased, potentially due to increased surface area promoting gastric digestion and nutrient release. Adding extruded RB (5%, 10%, 15%, 20%) to plant-based meat resulted in a more stable molecular conformation and improved antioxidant capacity attributed to phenolic and polypeptide compounds containing phenolic groups. This enhanced antioxidant capacity was achieved by forming more unstable t–g–t structures in disulphide bonds and disruptions in the protein's hydrophobic core, exposing hydrophobic amino acids that can react with oxidants.[64] Including DRB (25%, 40%, 55%) in soya protein isolates[30] and 20%, 35%, and 50% DRB in soya protein isolate and rice protein isolate was studied.[69] The conformational change in the protein from a β-sheet to a random coil and α-helix was due to the breakage of chemical bonds between protein molecules and protein denaturation was due to the extrusion process and unfolded protein. The protein solubility of soya protein isolates may decrease with the addition of RB.[69] Using extruded RB in various food products showcases its potential to enhance the end products' nutritional and functional aspects. The application of RB spans a range of food items, from noodles to protein-rich foods, with effects on sensory attributes, texture, and structural properties. Careful consideration of processing conditions and incorporation levels is essential to balance improved nutritional quality and optimal sensory experience.

7. SWOT analysis

A SWOT analysis is a strategic tool used to evaluate the internal strengths and weaknesses, and external opportunities and threats of an initiative. In utilising RB in the extrusion process, conducting a thorough SWOT analysis can provide valuable insights for informed decision-making. The analysis is aimed at identifying areas that require improvement and strategies to mitigate potential risks, all contributing to achieving desired objectives.

RB offers several advantages in extrusion. Its richness in feruloyl arabinoxylan can yield feruloyl oligosaccharides (FOs) through enzymatic extrusion.[59] This enhances its functional properties and reduces antinutritional factors like phytates,[62] making it valuable for various food applications. Extrusion technology allows for the incorporation of RB into a wide range of foods, including meat analogues, biscuits, cookies, cakes, noodles, bread, pasta, and extrudates. Extrusion of RB improves product attributes, such as texture and structural properties, antioxidant activity, and phenolic content.[33]

However, there are challenges associated with using RB in extrusion. The quality of expanded extrudates containing RB depends on various process variables, such as extrusion temperature, screw speed, feed moisture, and composition. Incorrect settings of these variables can lead to quality issues, as discussed earlier. The extrusion process can result in partial or complete denaturation of RB proteins, causing changes in amino acid content, especially tyrosine, tryptophan, and structure.[68] There is also the potential for nutrient loss, including phenolics, flavonoids, γ-oryzanols,[57] and vitamins (Vit. B1 and Vit. B2) during extrusion.[70]

RB offers several opportunities in extrusion. It can be used as a functional food ingredient, converted into soluble dietary fibre,[41] and yield increased fermentable sugars.[59] Extrusion-induced phytate hydrolysis in RB enhances mineral

- Rich in essential nutrients, like fiber, fats, protein, vitamins, and minerals that enhance the nutritional profile of the extruded food.
- The presence of tocopherols, tocotrienols, and gamma oryzanol, antioxidant activity is high in RB-incorporated foods
- Due to higher dietary fiber content, it promotes health by regulating, bile salt, blood sugar, and cholesterol.
- Due to the prolific nature of the starch, protein, and fiber, desired crispness, springiness, hardness, chewiness, and cohesiveness can be achieved.

- High-fat content in the RB can lead to increased stickiness and reduced expansion and difficulties in maintaining the textural properties.
- Large and non-uniform particle size (polyhedral starch granules of starch) of the RB impacts the flowability and uniformity of the extruded product
- Due to the distinct taste and aroma of the RB, formulation adjustment is necessary for consumer acceptance
- Free fatty acids and lipid oxidation can harm the aroma flavor and shelf-life of the product

- RB addition in food can be effective to address the growing consumer demand for high-fiber foods
- Incorporating RB into extruded foods provides an opportunity to reduce food waste, improve resource efficiency, and promote the economy.
- It is a valuable ingredient for developing gluten-free and allergen-free extruded products
- Being the by-product, it can be cost-effective in promoting the SDG's goals.

- The presence of fats can lead to issues such as increased stickiness, reduced flowability, and difficulties in achieving proper expansion and texture
- Proper storage, packaging, and antioxidant strategies like stabilization should be employed to minimize oxidation and maintain product quality
- Uneven distribution of RB particles within the extruded product can lead to variations in texture and appearance.
- Careful formulation and flavor masking techniques may be necessary to improve consumer acceptance.
- Limited availability or fluctuations in supply may impact the feasibility and cost-effectiveness of using RB in food extrusion.

Fig. 7 SWOT analysis for the use of rice bran in extrusion.

availability, including copper and zinc, potentially improving the nutritional content of food products.[62] Extrusion also boosts the soluble pentosan, soluble dietary fibre, and soluble starch content in RB.[41] Modified RB, achieved through a combination of extrusion and ball milling, results in a smaller particle size (24.79 μm).[26] This reduction in particle size and improved dispersion and stability offers opportunities for 3D printing of RB with hydrocolloids like starch, pectin, gelatin, nanocellulose, alginate, and carrageenan.[71]

However, there are challenges and threats to using RB in extrusion. Raw RB has low solubility and a rough taste due to its high dietary fibre content,[7] making it difficult to achieve proper expansion and texture.[39,49,50] For a comprehensive assessment, refer to the SWOT analysis for the utilization of RB in extrusion presented in Fig. 7.

8. Future prospects: circular food systems and sustainable intensification

The future of the rice industry seems to be heading toward developing and implementing novel, environmentally friendly techniques to upcycle its bran that can ensure the safety and quality of the products with adequate shelf life. Thanks to its extrusion potential, RB is poised to become a superfood. RB can be extruded to get snacks fortified with vitamins, minerals, and protein, packing a nutritional punch with improved taste, which could cater to diverse dietary needs. It does not stop at snacks only. It can be used as a filler in baked goods, meat alternatives, and even pasta, reducing reliance on other ingredients. Extrusion unlocks a spectrum of textures, from crispy puffs for breakfast cereals, and chewy bites for energy bars to resiliently tender meat analogues. The possibilities are endless for catering to every palate and meal occasion. Food waste can be minimized, diverting a valuable resource from landfills that aligns with the growing demand for sustainable food systems. Extruded RB acts as a flavour canvas, readily absorbing and releasing different seasonings. The hypoallergenic nature of RB makes it suitable for people with gluten sensitivities or celiac disease. Extruded RB products can offer delicious and safe options for those seeking alternative dietary staples. The application of extrusion in RB aligns perfectly with the principles of the circular economy, where food waste and by-products are recovered and valorised.[72] This reduces waste generation and creates new revenue streams for rice producers and processors.

RB extrusion contributes to sustainable intensification by maximizing resource utilization and minimizing environmental impact. The process requires less water and energy, reducing the environmental footprint of food production. Additionally, extruded RB offers enhanced digestibility and nutrient bioavailability,[58] improving feed efficiency and reducing reliance on resource-intensive animal protein sources. This aligns with the United Nations Sustainable Development Goal 1 (no poverty) by creating affordable food, Goal 2 (zero hunger) by improving food security, Goal 3 (good health and well-being) by enhancing bioactive compounds, and Goal 12 (responsible consumption and production) by valorising a by-product.[73] In conclusion, RB extrusion is an appropriate technology for circular strategies and sustainable intensification to generate positive outcomes for both the environment and food security.

The future of food with RB extrusion is brimming with possibilities. The general step-up approach for implementing the use of extrusion technology for RB is presented in Fig. 8. It is about sustainability, inclusivity, and delicious innovation. Extruded RB can be tailored to individual dietary needs and preferences, offering customized nutrient profiles and textures. This opens doors for a future of precision food tailored to each person's unique health requirements. As research and development continue, even more, exciting applications are sure to emerge, shaping the future of food in different ways. Extrusion parameters like temperature, pressure, moisture content, and

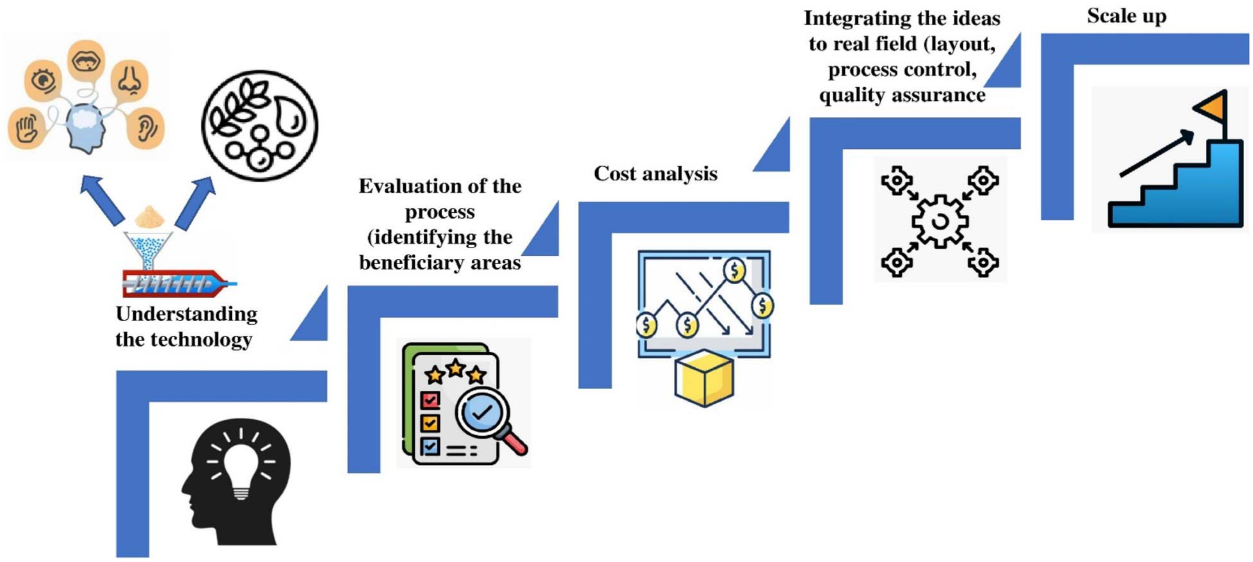

Fig. 8 General step-up approach for implementing extrusion technology with rice bran.

screw configuration play a crucial role in shaping the final product. Optimisation is essential to ensure desirable textures, nutritional retention, sensory parameters, and overall product quality. Target markets, product applications, and competitor landscape should be studied thoroughly. The potential challenges, risks, and areas for improvement should be identified through process evaluation.

Similarly, a cost analysis can be used to assess the benefits and return on the investment. Integrating ideas involves designing the physical infrastructure for production, implementing quality control measures, and developing protocols for operating the technology in a real-world setting. Scaling up is an iterative process. We should be prepared to adapt, refine, and continuously improve our approach based on data, feedback, and market trends.

9. Conclusion

Integrating RB into food formulations for extrusion presents many benefits. Notably, RB significantly enhances the nutritional value of extruded foods through its abundant dietary fibre, protein, vitamins, and minerals. Additionally, RB acts as a functional ingredient due to tocopherols, tocotrienols, and gamma oryzanol. This dynamic combination enables the creation of wholesome products that align with the increasing consumer demand for healthier food options. Furthermore, the utilization of RB underscores a commitment to sustainable practices, as it is derived from a by-product of rice processing, effectively curbing food waste. This innovative approach extends to various food products, including noodles, biscuits, cookies, cakes, and protein isolates, through upcycling. Particularly, the adaptability of modified RB extends to even 3D food printing following the modification of its fibre and starch. The incorporation of RB influences the extrusion processing parameters and properties of the extrudates. These factors also influence the conformational shifts within protein structures and the reduction of phytates while concurrently supporting the availability of antioxidants. It remains vital to address the potential challenges related to oxidation and rancidity despite the inherent inactivation of lipase at elevated extrusion temperatures. Realising the potential of RB in food is not without challenges, where processing difficulties, sensory acceptance, and potentially lower expansion represent critical considerations. However, proactive steps, including meticulous formulation, optimisation of processing parameters, stringent quality control measures, and comprehensive consumer testing hold promise for effectively addressing these challenges. In summary, the combination of RB within food extrusion offers a promising avenue for creating nutritionally enriched and functionally versatile extruded food products that cater to evolving consumer palates and preferences. As the gastronomic landscape continues to evolve, RB stands poised to play a pivotal role in shaping the future of wholesome and sustainable dietary offerings.

Conflicts of interest

The authors declare no potential conflict of interest.

Data availability

No data was used for the research described in the article.

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