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REVIEW PAPER

AN OVERVIEW ON EXTRUDED RICE ANALOGUES PRODUCED USING HOT EXTRUSION PROCESSING

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Abstract

The development of extruded rice analogues using hot extrusion processing has gained significant attention due to its potential to address food security and meet consumer demands for functional and nutritious foods. This review provides a comprehensive overview of the key aspects involved in the production and characterization of extruded rice analogues. The ingredients used in the extrusion process are discussed, highlighting their roles in determining the final product properties. The thermal and pasting properties are reviewed, emphasizing their product stability and functionality implications. The texture profiles, including hardness in uncooked extruded rice analogues and texture changes upon cooking, are critically reported. Furthermore, cooking behavior, nutritional value, and sensory properties of extruded rice analogues are summarized to assess their acceptability and suitability for diverse consumer groups. The review also explores market opportunities and challenges, identifying pathways to improve product development and commercialization. In conclusion, this review focuses on the prospect of extruded rice analogues being a sustainable and approach to diversification of food product.

Keywords: Extruded rice analogues, hot extrusion, pasting profile, thermal properties

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Introduction

Food diversification is an initiative to generate, distribute, and consume various alternative food choices from local sources (sago, corn, tubers, and others). Food diversification aims to eliminate reliance on rice consumption by producing, distributing, and consuming various other foods made from locally available resources to strengthen national food security (Pudjihastuti *et al*., 2019a). Extruded rice analogue (ERA) manufacturing has become a viable alternative to address these changing demands. Extruded rice analogues can be eaten by consumers similarly to how native rice is prepared. Extruded rice analogue is illustrated as rice-shaped grains formulated from non-rice ingredients to meet human energy and protein (Sukamto, 2018). Extruded rice analogue products are projected to contribute to the national food stability program by decreasing rice consumption levels without altering the dietary customs of the societies while continuing to meet their carbohydrate requirements (Noviasari *et al*., 2017). Typically, researchers enhance artificial rice by adding functional ingredients, converting it into a nutritious food that provides health benefits and more excellent nutritional value than native rice. These characteristics provide an advantage and strength in the market, particularly for health-conscious individuals and those with specific health concerns, such as diabetes, who prefer consuming extruded rice analogues over traditional rice (Valencia and Purwanto, 2020).

Extruded rice analogues can be made from rice flour wholly or partially broken down from non-rice ingredients (Mishra *et al*., 2012). Meanwhile, according to Budijanto and Yuliyanti (2012), extruded rice analogues are artificial rice shaped like rice grains, which can be made from non-rice flour with water. Extruded rice analogues are foods that are similar in texture and form to rice and are created from broken rice or any other source of carbohydrates (Budi *et al*., 2017). Another advantage is that extruded rice analogues can be cooked and consumed like rice from paddy with side dishes (Noviasari *et al*., 2017). Extruded rice analogue production technology can be achieved using granulation, hot extrusion, and cold extrusion processes (Sumardiono *et al*., 2021). Numerous research studies on extruded rice analogues have employed the granulation technique. Nonetheless, the attributes and appearance of extruded rice analogues continued to fall short of the panelists' expectations (Kusumayanti *et al*., 2023).

Hot extrusion processing has developed as an essential approach in manufacturing extruded rice analogues. In hot extrusion, dough is processed at high temperatures (>70 °C) using preheated steam barrels. Hot extrusion processing is commonly used to precook extruded rice analogue grains to shorten the cooking time (Mishra *et al*., 2012). Hot extrusion can create extruded rice analogues resembling paddy rice's shape and cooking quality. It enables the utilization of diverse raw materials and is viable for implementation in industrial operations of medium to large size. According to Budijanto and Yuliana (2015) and Chaturvedi and Manickavasagan (2024), some benefits of using the hot extrusion method are: producing extruded rice analogues with shapes and sizes similar to the native rice, similar to paddy rice in terms of cooking quality and it can be utilized in medium-to-large-scale production capacities and adopted by medium- to large-scale industries. It requires only five to ten minutes to cook. Sule *et al*. (2024) also explained that the benefits of the hot extrusion method enable the production of porous and expanded materials, and this can involve partial denaturation of proteins, cooking or gelatinization, and producing cooked or partly cooked products with specific characteristics and textures.

The extruder is comprised of a cylindrical tube containing a helical screw, which can be either a single screw (single screw extruder) or two screws (twin screw extruder). The single screw extruder is commonly employed in food manufacturing due to its cost-effectiveness and user-friendly operation. Extruded rice analogue products typically have a texture close to standard rice, primarily because of a higher level of starch gelatinization during the hot extrusion process. To undergo gelatinization, the hydrogen bonds within the amorphous region need to be initially disrupted and subsequently hydrated with water. These phases result in the release of amylose, the disruption of granules, and the formation of a colloidal gel structure (Mostafa and Naseef, 2022). The gelatinization process is affected by the ratio of amylose to amylopectin. The optimal amylose-to-amylopectin ratio for achieving a successful gelatinization process is between 1:3 and 1:5. An excessive amount of amylose will lead to a loss in development power. In contrast, an excessive amylopectin ratio will increase rice's resilience (Sasaki and Matsuki, 1998). Elevated temperature, prolonged retention time, and increased screw rotation speed enhance the viscoelastic properties of the gelatinization outcomes while diminishing the intrinsic value of the final product's color (Navale *et al*., 2015).

Ingredients for the process of extrusion

Extruded rice analogues are artificial duplicates of native rice composed of 50-98% starch or its derivatives, 2-45% additives that enhance the nutritional value of the extruded rice analogues, and 0.1-10% hydrocolloids (Dwiutami *et al*., 2023). Different combinations of raw materials, such as cereals, grains, starches, tubers, oilseeds, legumes, and proteins, are used in extrusion cooking (Offiah et al., 2019). These materials' type, physical condition, pH, moisture content, and chemical constituents (starch, proteins, and lipids) are essential aspects that distinguish products (Sule *et al*., 2024). They are divided into groups according to their functional functions, which include preservatives, plasticizers, dispersion phase fillers, coloring materials, flavoring agents, and structure-forming components (Singh *et al*., 2017; Sule *et al*., 2024).

Recently, significant research has been conducted into creating rice substitutes that enhance protein and nutritional levels. Researchers have found that protein-rich cereal and pulse-based flours are ideal ingredients for producing extruded rice analogues using methods such as extrusion. Formulating nutritious extruded rice analogues is contingent upon its constituents' specific composition. A typical extruded rice analogue consists of a main ingredient (often a starch and/or protein-rich alternative source), water (in appropriate amounts), and additional additives such as coloring and flavoring compounds, binders, agents that help the binders set, fortifying substances, lubricants, and antioxidants (Chaturvedi and Manickavasagan, 2024). Scientists have examined the potential of many ingredients, including sorghum, arrowroot, soybean, modified cassava, cornflour, peas, and bean-based flours, to be utilized as the primary component in producing extruded rice analogues rich in protein or nutrients. Table 1 shows the nutritional characteristics the extruded rice analogues as presented by studied literature. Cassava flour is a commonly used ingredient for producing extruded rice analogues. Modified cassava flour (Mocaf) is made from genetically modified cassava. Nevertheless, the protein content in Mocaf constantly remains below 0.5%. Therefore, subsequent research has begun investigating adding extra components to improve the overall nutritional content of the cassava flour-based extruded rice analogues. A study conducted by Sukamto and Patria (2020) by combining cassava flour, sorghum, sweet potatoes, and corn with lablab bean, and soybeans resulted in extruded rice analogues with high nutritional components, such as moisture content 9.87-12.05%, protein 10.39-13.08%, lipid 4.87-5.87%, ash 0.72-1.66%, crude fiber 7.92-9.51%, and carbohydrate 66.23-57,83%.

Recent studies have demonstrated that by combining corn flour with various cereal-based flours, such as arrowroot starch and soybean flour (Supadmi *et al*., 2023), mung bean flour (Rumitasari *et al*., 2022), by using suitable amounts, it is possible to create extruded rice analogues that have a satisfactory nutritional and sensory profile, as shown in Table 1. However, Budi *et al*. (2015a) focused on creating extruded rice analogues from yellow corn flour and corn starch. They aimed to develop a nutritious alternative to rice that had desirable dough qualities and was produced under optimized extrusion settings.

Numerous investigators have explored the possibilities of sago as a primary ingredient for extruded rice analogues. Nugraheni *et al*. (2020) conducted a study to examine how the composition of composite flour (sago starch, arrowroot flour, germinated red kidney bean flour, and germinated white sorghum flour) affect the nutritional value and overall sensory acceptance of extruded rice analogues. The study findings indicated that a combination of 6% sago starch, 5% arrowroot flour, 4% germinated red kidney bean flour, 4% germinated white sorghum flour, and 1% modified arrowroot flour resulted in the highest quality attributes and consumer acceptability. Nugraheni *et al*. (2022) also conducted a study to examine how the composition of sago flour, in combination with cassava flour, modified cassava, germinated soybean flour, and germinated sorghum flour, affects the physicochemical properties of extruded rice analogues.

Lalel *et al*. (2024) studied the possibility of obtaining extruded rice analogues by mixing Gebang starch and mung bean flour in different quantities. Increasing the mung bean ratio increased protein content from 2.18 to 6.95%. The obtained final products had similar dimensions to native rice, with 7mm in length and 3 mm in thickness. A different study also found that combining sago flour, arrowroot tuber flour, and mung bean flour yielded the best results. This study's recommended extruded rice analogues contained 11.18% water content, 80.27% carbohydrates, 5.14% protein, 0.46% fat, and 5.14% crude fiber (Sumardiono *et al*., 2022). Extruded rice analogues from seaweed (*Sargassum* sp.) and beneng taro flour produced a high dietary fiber content of 18-19% (Aditia *et al*., 2023). Darmanto *et al*. (2022) made extruded rice analogues from arrowroot and seaweed flour fortified with fish collagen. Collagen supplementation effectively enhanced the concentration of individual amino acids in extruded rice analogues. Extruded rice analogues with substitution of Moringa leaf flour mixed with sorghum flour, Mocaf, and glucomannan extract from porang tuber, showed significant differences in total dietary fiber, soluble dietary fiber, and insoluble dietary fiber content (Wahyuningsih *et al*., 2023).

Table 1. The nutritional content between rice and extruded rice analogues.

Nutritional content of extruded rice analogues						
Moisture (%)	Protein (%)	Lipid (%)	Ash (%)	Crude fiber (%)	Carbohydrate (%)	References
			Rice			
White rice						
14	5.2-7.1	0.2-1.1	0.31-0.70	0.2-0.6	78-85	(Chaturvedi and Manickavasaga, 2024)
Brown rice						
14	5.5-8.3	2.4-3.7	0.83-1.79	0.7-1.0	71-78	
Parboiled rice						
-	8.38-11.34	2.16-3.80	0.45-2.46	-	83.19-86.51	(Muchlisyiyah *et al.*, 2023)
			Extruded rice analogues - ingredients			
Gebang starch and mung bean flour						
6.79-9.05	2.18-6.95	0.10-0.14	0.75-1.12	-	83.36-87.98	(Lalel *et al.*, 2024)
Mocaf, arrowroot, and red bean flour						
12.19	6.17	1.38	2.64	-	89.88	(Wahjuningsih & Susanti, 2018)
Modified cassava flour (Mocaf) and snakehead fish flour (SF)						
14.25	7.95-10.22	0.73-1.02	0.63-1.08	2.92-3.94	70.56-72.22	(Sumardiono *et al.*, 2020)
Cassava flour, sorghum, sweet potatoes, corn + lablab bean, and soybeans						
9.87-12.05	10.39-13.08	4.87-5.87	0.72-1.66	7.92-9.51	66.23-57,83	(Sukamto and Patria, 2020)
Modified cassava flour, mung bean flour, and purple corn flour						
8.60	11.34	1.52	1.52	-	73.62	(Sada *et al.*, 2021)
Cassava flour, avocado seed flour, and tofu waste						
0.97-12.58	0.19-16.50	0.06-7.39	0.20-192	0.40-26.98	62.31-80.76	(Putri and Sumardiono, 2020)
Corn flour, arrowroot Starch, and soybean flour						
9.58	9.54	3.19	1.15	5.53	76.54	(Supadmi *et al.*, 2023)
White corn and mung bean flour						
8.40	13.60	1.30	1.60	5.70	75.10	(Rumitasari *et al.*, 2022)
Sago starch, arrowroot flour, germinated red kidney bean and white sorghum flours						

9.71	8.04	1.01	3.38	19.81	68.74	(Nugraheni *et al*., 2020)
Sago starch, cassava flour, modified cassava, germinated soybean and sorghum flours						
6.41-9.80	7.72-11.04	0.55-1.11	2.12-2.53	7.72-9.49	68.91-7050	(Nugraheni *et al*., 2022)
White rice, modified cassava flour (Mocaf), and cassava leaves powder						
8.3-9.5	8.01-12.77	0.73-4.27	1.16-1.65	1.46-3.84	72.99-79.45	(Liu *et al*., 2022)

Binding agents are another crucial component needed to prepare extruded rice analogues, which make it easier to combine all the ingredients in the mixture regardless of variations in the dough's temperature and moisture content. Adding glycerol monostearate (GMS) improved textural characteristics, the obtained values being similar to those of native rice (Pudjianto *et al*., 2023). Incorporating carboxymethyl cellulose (CMC) into the extruded rice analogue formula directly impacts its chewiness by enhancing its firmness and texture while elevating its fiber content (Sumardiono *et al*., 2021). Starch, polysaccharides, and hydrocolloids (such as sodium alginate and xanthan gum) can interact with other substances in an aqueous solution. Covalent interaction between molecules and the interconnected bonds of molecular chains create a network structure that increases fluid viscosity or forms a gel (Peng *et al*., 2020).

Thermal properties of extruded rice analogues

Assessing the stability of the materials within the extruded rice analogue matrix during processing and storage is a crucial aspect of extruded rice analogue production. Several recent studies have concentrated on using the glass transition to evaluate the stability of the food and its constituents. The glass transition is also associated with foods' molecular mobility, chemical reactions, and shelf life (Herawat *et al*., 2014). Differential scanning calorimetry (DSC) is commonly used to investigate the thermal characteristics of starches. DSC data can be utilized to accurately measure the extent of gelatinization, retrogradation, and phase transitions in starches derived from maize, wheat, and rice. Thermal treatment causes gelatinization (swelling of starch with excess water) and dextrinization (structural damage to starch with low moisture). Gelatinization happens when starch molecules undergo a thermal transition in response to temperature and moisture content changes. The starch changes throughout this process from a semi-crystalline to an amorphous form. The hydrogen bonds are disrupted in abundant water, enabling water molecules to form bonds with the unoccupied hydroxyl groups. This alteration, therefore, permits the grains to expand and increases their molecular mobility in the amorphous areas (Kaur *et al*., 2016).

The focus of the DSC measured gelatinization process was on the endothermic transition curve. The temperature is the primary determinant in the investigation of gelatinization. In the process of gelatinization, the term "To" refers to the initial temperature, "Tp" represents the beginning of gelatinization or crystal melting, and "Te" denotes the final temperature. The energy required to complete the gelatinization process represented as enthalpy change, "ΔH," is equally significant (Rohaya et al., 2013). The gelatinization process/enthalpy change "ΔH" indicates the extent to which starch granules have undergone gelatinization. A higher gelatinization temperature and ΔH suggest that a higher temperature is required to break down the crystalline structure of starch molecules, indicating that starch is more susceptible to retrogradation (Liu *et al*., 2024). Table 2 shows the thermal characteristics of some extruded rice analogues as reported in the studied literature. The lower values of extruded rice analogues in onset temperatures (To) and peak temperatures (Tp) suggest that the hydrogen bonds between starch molecules in extruded rice analogues were disrupted, leading to the disintegration of most of the crystal structure resulting from extrusion. The transition of starch from an organized state to a disorganized state resulted in a significant reduction in the required heat energy throughout the DSC measurement method. Others have reported similar findings that the higher the enthalpy (ΔH), the more energy is needed for the gelatinization of starch (Wang *et al*., 2010). The lower ΔH value suggests that less energy was employed to disrupt the internal bonds of starch molecules (Wang *et al*., 2021). Sandhu and Singh (2007) explained that the higher gelatinization onset temperature (To) and peak gelatinization temperature (Tp) indicated that more energy was required to initiate starch gelatinization. The difference in ΔH reflected the melting of amylopectin crystallites. It could represent a difference in bonding forces between the double helices that form the amylopectin crystallite, which results in different alignments of hydrogen bonds within starch molecules (Budi *et al*., 2015a). In addition, Na-Nakorn *et al*. (2021) discussed that the water absorption property of the protein likely contributed to the shift in the onset transition temperature (To), peak temperature (Tp), and conclusion temperature (Tc) of extruded rice analogues to higher temperatures, resulting in a decrease in the availability of water for the gelatinization process. These results are similar to those found in other studies (Li *et al*., 2007; Yu *et al*., 2015).

The decreased To, Tp, and Tc values of extruded rice analogues may be attributed to either greater water availability for starch gelatinization or the enhanced surface area of flour particles, facilitating water penetration into rice starch granules. According to Kumoro and Noprastika (2017), extruded rice analogues containing a significant amount of amylose have elevated gelatinization temperatures. Rice varieties with a higher amylose content have a greater capacity to absorb water while cooking, leading to higher gelatinization temperatures. Consequently, these types of rice require a longer cooking time compared to varieties with a lower gelatinization temperature. Similar results of a study on maize starches with varying amylose content indicated that the gelatinization temperatures increased with increasing amounts of amylose (Park *et al*., 2007). Sasaki *et al*. (2000) explained that starch with higher amylose content contains more amorphous and less crystalline regions, leading to a lower gelatinization temperature and enthalpy. Furthermore, the gelatinization temperature of extruded rice analogues may have been influenced by additional factors, such as starch structure and nutritional properties. Wang et al. (2023) studied the interaction between rice starch and glutelin in the preparation of reconstituted rice. The Tp of reconstituted rice decreased from 124.23◦C to 104.68◦C, and the ΔH value decreased from 339.8 J/g to 212.2 J/g. This indicates that less energy was needed for starch gelatinization and glutelin denaturation. The breaking and disintegration of hydrogen bonds during extrusion can destabilize the crystalline structure in rice starch. Consequently, it reduces the stability of both the crystalline and amorphous areas inside the granule. Wirjosentono *et al*. (2020) explained that negative enthalpy values ΔH indicate an endothermic process, which requires energy absorption from the surroundings. The value of -109.18 J/g represents the energy needed for the starch gelatinization process or the substance's structural transition.

Table 2. Thermal properties between rice and extruded rice analogues.

To (°C)	Tp (°C)	Te (°C)	ΔH (J/gm)	References
Rice				
White rice				
60.07-60.88	77.98	69.81-70.13	3.25-7.72	Mogoginta *et al*., 2024)
Brown rice				
59.36	65.84	78.11	9.91	(Lin *et al*., 2023)
Parboiled rice				
43.80	44.70	51.50	2.37	(Kumar and Prasad, 2018)
Extruded rice analogues - ingredients				
Cassava Starch, corn powder, and taro powder				
75.90	107.48	151.77	-109.18	(Wirjosentono *et al*., 2020)
Broken indica rice flour and purple sweet potato powder				
73.69	78.05	82.80	2.55	(Wang *et al*., 2021)
Yellow corn flour and corn starch				
62.87	72.68	81.90	5.88	(Budi *et al*., 2015a)
Extruded rice flour supplemented with soy protein isolate				
74.70	79.10	81.90	1.30	(Na-Nakorn *et al.*, 2021)
Breadfruit flour, mung bean flour, and carrot flour				
73.61	78.20	81.61	-	(Kumoro and Noprastika, 2017)
Rice starch and glutelin				
50.40 - 73.93	104.68-124.23	204.58-247.00	212.2-339.8	(Wang *et al*., 2023)
Native Malaysian rice				
64.52	70.58	79.34	0.80	(Hashim *et al*., 2020)

Pasting properties of extruded rice analogues

The pasting characteristics of extruded rice analogues were typically assessed using a rapid visco analyzer (RVA). The viscosity measurements, including peak viscosity

(PV), trough viscosity (TV), breakdown viscosity (BD), final viscosity (FV), and setback viscosity (SB), were recorded during this process. Assessing the pasting characteristics is crucial as it can assist in determining the cooking stability, water absorption capacity, and baking performance of starch. The qualities of the paste used heavily influence the quality of rice or rice-based food products. In addition to the physical, textural, and gelatinization features, the starch components of rice can also significantly impact the quality of a rice product. Starch is a crucial constituent of rice grains and substantially affects the texture of cooked grains. Understanding the adhesive qualities of rice is a technique used to gather fundamental information that might be used in developing novel food products or formulations of rice-based products (Thomas *et al*., 2014). Nevertheless, native rice starch is challenged by many drawbacks, including limited water absorption, water solubility, and significant retrogradation when stored. With the extension of storage time, rice became harder due to the retrogradation of the rice starch, thereby significantly shortening the shelf life (Liu *et al*., 2024). Table 3 shows some pasting characteristics of different extruded rice analogues formulations.

Wahjuningsih and Susanti. (2018) manufactured extruded rice analogues using Mocaf, arrowroot, and red bean flour. The study emphasized that heat during gelatinization leads to the permanent expansion of starch granules in water, resulting in an elevation in viscosity. The gelatinization temperature of the material determines the optimal temperature for extrusion, as partial gelatinization may occur before the extrusion process. Amylose can bind with protein and fat, causing precipitation and raising the gelatinization temperature.

Table 3. Pasting properties between rice and extruded rice analogues.

Pasting temp (C)	**Peak time (min)**	**Peak viscosity (cP)**	**Breakdown (cP)**	**Final viscosity (cP)**	**Setback (cP)**	**References**
			Rice			
White rice						
82.35	6.07	4149	1402	6921	4147	(Kumar & Prasad, 2018)
			Brown rice			
84.8-88.1	5.29-5.82	1254-1569	48-440	2563.7-4157	1419-2714	(Chapagai et al., 2020)
Parboiled rice						
85.60	6.13	2378	182	4254	2059	(Kumar & Prasad, 2018)
			Extruded rice analogues - ingredients			
Mocaf, arrowroot, red bean						
68.4	6.6	5663	3655	3394	1386	(Wahjuningsih and Susanti, 2018)
Broken rice flour and broken pigeon pea dhal flour						
78.68	-	23173	-	-	-	(Ganachari *et al*., 2022)

Fermented cassava (Oyek) enriched with isolated soy protein						
65.48	-	-	-	-	-	(Rahmawati *et al*., 2019)
Sago-red rice						
80.60	4.87	3234	1380	2704	850	(Puspantari *et al*., 2023)
Sago- corn						
79.90	4.27	1384	684	1071	371	(Puspantari *et al*., 2023)
Sago-black rice						
80.80	5.07	2002	839	1832	669	(Puspantari *et al*., 2023)
Sago-read bean						
79.05	4.00	2195	1234	1613	652	(Puspantari *et al*., 2023)

The amylose content of arrowroot flour exceeded that of Mocaf flour, potentially resulting in the disparity in gelation temperature between the two substances. The amyloses that are oriented in chains and form crystallites with double strands exhibited resistance to amylases. Hydrogen bonding within and between strands results in a hydrophobic structure that exhibits limited solubility. Heating starch in an adequate amount of water disrupts the firmness of the double helix structure formed by hydrogen bonding in the crystalline form of starch. The formation of hydrogen bonds between water molecules causes this disruption. As a result, amylose is released from the starch granules. After that, amylose and amylopectin would hydrate; therefore, viscosity will increase until it peaks, and starch suspension will become clearer (Schirmer *et al*., 2013). The peak viscosity demonstrated the starch's capacity to expand without restriction before disintegration. The levels of amylose and amylopectin in the material influenced the peak viscosity. Increasing the amylose content results in a decrease in peak viscosity. This was caused by amylose and fat binding to form amylose lipid complexes so that granule swelling was suspended (Sang *et al*., 2008).

The pasting temperature (PT) represents the lowest temperature necessary to cook the flour. The highest PT in flour indicates the presence of starch that is highly resistant to swelling and rupturing (Kaushal *et al*., 2012). Ganachari *et al*. (2022) studied the development of extruded rice analogues using by-products of rice and dhal mills. The PT raised proportionally with the addition of pigeon pea dhal flour. The alterations in the adhesive characteristics can be attributed to the increased ability of the protein found in pigeon peas to expand. The presence of abundant protein and starch in the flour may result in the starch granules becoming trapped within a rigid protein structure, thereby limiting the absorption of moisture by the starch and inhibiting its expansion. Rahmawati *et al*. (2019) studied the development of rice substitute products using fermented cassava (Oyek) enriched with isolated soy protein. A lower pasting temperature suggests that starch can be gelatinized more rapidly, resulting in a significantly quicker cooking time. This has the potential to create instant artificial rice. Peak time (Pt) indicates the minimum time required to cook the flour (Anberbir *et al*., 2024). Sompong *et al*. (2011) reported that rice with high amylose content peaks above 8 minutes.

Peak viscosity (PV) is the significant rise in viscosity when a sufficient number of granules in a sample expand. The peak viscosity negatively correlated with the higher levels of broken pigeon pea dhal flour (BPDF) and moisture content (Ganachari *et al*., 2022; Kaushal *et al*., 2012). An increase in viscosity as temperature rises may be attributed to the granules' water absorption from the extruded amylose, causing them to expand. The ability of flour to increase in size is directly linked to the amount of protein and starch they contain. A significant amount of protein in the flour can result in the starch granules being trapped within a rigid protein structure, which hinders the starch's ability to absorb water and expand. The elevated swelling ability of rice and taro flours can be attributed to their low protein and high carbohydrate contents. The bonding forces present within granules may also influence their swelling characteristics. The weaker bonding forces in rice permit higher swelling and, consequently, higher PV than stronger bonding in pigeon pea flour (Kaushal *et al*., 2012). The decrease in peak viscosity after expansion can be attributed to the alteration of the internal molecular structure, weakening of hydrogen bonds, and disruption of the crystal structure caused by elevated temperatures. High temperature weakened the solution's shear hindrance and reduced viscosity (Zhang *et al*., 2020). Trough viscosity (TV) refers to the specific point during heating or cooling procedures when the viscosity of a substance reaches its lowest value. It measures the ability of the paste to withstand breakdown during cooling. The rate of amylose exudation, granule swelling, and amylose lipid complex formation influences trough viscosity (Sangeeta and Grewal, 2018). Karakelle *et al*. (2020) demonstrated a negative correlation between amylose content and TV value.

Breakdown viscosity (BV) measures starch's disintegration ability (Yadav *et al*., 2022). The smaller BV values indicated better thermal stability and stronger shear resistance of the samples (Onwulata *et al*., 2014). BV results from the disruption of inflated starch granules, which causes the release of amylose during the holding phase at 95°C under shear. High values of BV indicate the lesser breakdown of starch and are somewhat inferior in handling heating and sheer stress during cooking (Thomas *et al*., 2014). The final viscosity (FV) measures the material's thick and sticky paste capacity. Re-association of starch molecules occurs when the mixture is cooled, consequently forming a gel leading to enhanced viscosity (Kaushal *et al*., 2012). Final viscosity (FV) is commonly used as a quality parameter to measure the strength of a gel formed on cooling (Cornejo-Villegas *et al*., 2010). The rapid increase in FV could be attributed to the amylose chains attaining an ordered arrangement (Flores-Farías *et al*., 2000). During the cooling of starch dispersions, gelation occurs as amylose and amylopectin aggregate to form a gel network. However, higher protein content has been found to correlate with a reduction in final viscosity (Nilsson *et al*., 2023). During cooling, amylose in the starch paste retrogrades, and the viscosity increases to the final value; thus, the final viscosity is positively correlated to the amylose content (Tao *et al*., 2019). Setback viscosity

(SV) refers to the restoration of viscosity when a heated starch suspension is cooled. It measures the separation of starch following the cooling of cooked starch pastes. Setback viscosity (SV) indicates the syneresis of cooked starch during cooling (Yadav *et al*., 2022). Decreasing of Setback viscosity (SV), suggesting a lower tendency to retrograde. The Flour with the lowest setback and breakdown viscosities suggests that it has high resistance to retrogradation and, therefore, would form a stable paste (Kaushal *et al*., 2012).

A study conducted by Puspantari *et al*. (2023) about the characteristics of five formulations of sago rice has a peak viscosity ranging from 1384 to 3234 cP, breakdown viscosity ranging from 684 to 1380 cP, final viscosity ranging from 1071 to 2704 cP, setback viscosity ranging from 371 to 850 cP, the pasting temperature ranged from 79.05 to 80.80°C. Meanwhile, the viscosity profiles of white rice (local Malaysian rice) had a peak viscosity of 729 cP, breakdown viscosity of 345 cP, final viscosity of 1077 cP, setback viscosity of 561 cP, a peak time of 9.20 minutes, and pasting temperature of 73.50°C.

Texture of uncooked extruded rice analogues

Texture has a crucial role in how consumers perceive and accept food commodities. The primary consequence of the thermal-mechanical treatment caused by extrusion is the disruption of the granular arrangement of starch. In addition, the complex formation between amylose and lipids during extrusion cooking plays a vital role in the extrudate's structure, texture, and other functional properties (De Pilli *et al*., 2011). Kumoro and Noprastika (2017), in their study, explained that the hardness of the sample was assessed by quantifying the force necessary to fracture the rice counterparts. Lower strain and hardness values suggest the presence of more fragile and brittle particles with a higher level of porosity. The increased carbohydrate content in the dough is expected to result in rice mimics with elevated hardness properties. Modifying the free amylose to amylopectin ratio is likely responsible for the change in these properties since it leads to the formation of amylose-lipid complexes. The hardness values of the extruded rice analogues (1.60 MPa) were much lower than the hardness of paddy rice IR-36 (6.53 MPa) with a significant difference ($p < 0.05$) (Kumoro and Noprastika, 2017). Lower strain and hardness values suggest the presence of particles that are weaker, more brittle, and have a higher level of porosity. The amylose contents of the extruded rice analogues were are different significantly ($p < 0.05$), which is (15.88 %) lower than that of IR-36 rice (27.30 %) (Kumoro and Noprastika, 2017). Two potential reasons exist for the low amylose level in extruded rice analogues. The first reason is attributed to the degradation of amylose that occurs during the extrusion process. Amylose degradation is caused by the breakdown of amylose chains, which is hindered by the pressure inside the extruder, preventing the formation of helices. Another process that occurs during extrusion is the creation of a complex between amylose and lipids during extrusion. The decrease was directly proportional to the degree of complexing, which depends upon both starch and lipid type present in a food (Bhatnagar and Hanna, 1994).

Budi *et al*. (2015b) studied the effect of extrusion temperature and moisture content of corn flour on the crystallinity and hardness of extruded rice analogues, and found that the moisture content of the dough was found to have a decreasing effect on the hardness of extruded rice analogues, while the extrusion temperature had an opposite effect, tending to enhance the hardness of extruded rice analogues. The hardness of extruded rice analogues rose from 1.71 – 4.36 kg to 2.05 – 5.70 kg as the extrusion temperature was raised from 70ºC to 90ºC. Elevating the extrusion temperature led to an augmentation in crystallinity in rice analgoues. The formation of amylose and lipid complexes led to a more structured arrangement and enhanced intermolecular bonding, augmenting extruded rice analogues' firmness. The hardness of Malaysian rice was measured at 9.38 kg (Sathongpan *et al*., 2021), which is harder than that of the extruded rice analogues produced by Budi *et al*. (2015b). Extrusion is a common method used to produce rice analogues. This process involves high temperature and pressure, which can lead to changes in the rice's microstructure, such as a rougher surface and altered crystalline structure, resulting in a softer texture. In addition, a lower hardness level is preferable since it directly impacts the cooking qualities and results in less firm rice. Handayani (2017) explained that the hardness of sweet purple sweet potato extruded rice analogues varied from 8.42 N to 9.90 N. The amylose content is the factor that determines the texture of the rice. As the level of amylose in rice increases, it will have a more firm and consistent texture, and vice versa. The amylose concentration in sweet purple potato extruded rice analogues varied between 10.65% and 20.39% (Handayani, 2017). As the starch composition increases in extruded rice analogues, the amylose level also increases, resulting in a more complicated texture of the rice. Extruded rice analogues produced from sweet purple potato are classified as products with low amylose. Extruded rice analogue with low amylose content are fluffier and have a soft texture. The amylose concentration of native rice directly impacts the rice's quality and texture when cooked. Native rice with a low amylose content produces a sticky, tender, glossy texture and fails to expand or solidify upon cooling. In contrast, native rice containing higher amylose content is typically more resistant to hydration and gelatinization (Yadav and Jindal, 2007). This type of native rice also gives more viscous flour dispersion during water cooking and is firm and fluffy when cooked (Kumoro and Noprastika, 2017). In addition, Pudjihastuti *et al*. (2019b) stated that the higher the content of sago flour, the harder the extruded rice analogue. The high amylose concentration in sago starch provides a sticky and rigid structure. Minweyelet *et al*. (2021) studied the effects of extrusion operating conditions and blend proportion on the physicochemical and sensory properties of *teff*-rice blend extruded products. The highest hardness values recorded were 222.7 N for extrudates produced at a barrel temperature of 130°C, with a feed moisture level of 25% and 100% *teff*. On the other hand, the lowest hardness value was 60.23 N for extrudates produced at a barrel temperature of 150°C, with a moisture content of 21% and a mix ratio of 50% *teff* and 50% rice. This blend ratio was less rigid and required less force. The greater force needed to shatter the samples was seen as the proportion of *teff* and moisture content increased, and the extrusion temperature decreased. The possible cause of this phenomenon could be attributed to the high content of protein and fiber found in *teff*, leading to a decrease in expansion and an increase in density and hardness.

Texture of cooked extruded rice analogues

The textural quality of cooked extruded rice analogues assessed using texture profile analysis (TPA) are presented in Table 4. The analysis measures various parameters, including hardness, springiness, cohesiveness, adhesiveness, gumminess, and chewiness (Ramadhan *et al*., 2024).

Pudjianto *et al*. (2023) studied the extrusion process by incorporating 5% Glycerol Monostearate (GMS) into the texture of artificial rice (tiwul rice). Authors stated that adding 0.5% GMS to a mixture of dried cassava and corn flours for manufacturing "tiwul" rice can enhanced its hardness, cohesiveness, adhesiveness, springiness, gumminess, and chewiness. These characteristics were similar to those of native rice. Zhang *et al*. (2020) investigated the effect of adding calcium chloride on the adhesiveness and maximum adhesiveness of extruded rice analogues, while also observing a decrease in their elasticity. On the other hand, adding sodium alginate increased elasticity, chewiness, and extrusion work.

Table 4. Textural properties of cooked extruded rice analogues.

Texture profiles*						
H. (N)	**Adh. (mJ)**	**Coh.**	**Gumm. (N)**	**Che. (mJ)**	**Spr. (mm)**	**References**
Extruded rice analogues - ingredients						
Dried cassava flour, corn flour, and 5% of GMS						
66.63	23.56	0.15	14.84	11.54	0.77	Pudjianto *et al*., (2023)
Broken rice, foxtail millet, quinoa, and barnyard millet						
22.98	0.83	0.143	3.02	0.95	0.26	(Yadav *et al*., 2021)
Gracilaria sp, sago flour, rice flour, corn flour, glycerol monostearate, and palm oil						
10.52	71.30	0.60	-	4.29	0.69	(Ramadhan *et al*., 2024)
Rice flour, Mocaf, and 20% cassava leaves						
31.08	-15.56	0.44	-	7.18	0.53	(Liu *et al*., 2022)
Kodo millet semolina, rice flour, xanthan gum, and GMS						
14.91	0.80	0.23	-	0.74	0.83	(Karthik *et al*., 2024)
Soybean flour and corn starch and transglutaminase (TGase)						
423.10	-	0.45	-	2.11	1.12	(Sutrisno *et al*., 2024)

Malaysian Brown rice LS_1						
6.75	-0.18	0.16	-	-	-	(Chapagai *et al*., 2020)
Malaysian Brown rice LS_2						
9.91	-0.24	0.15	-	-	-	(Chapagai *et al*., 2020)

* Hrd. – Hardness; Adh. – Adhesiveness; Coh. – Cohesiveness; Gumm. – Gumminess; Ch. – Chewiness; Spr. - Springiness

A study conducted by Yadav *et al*. (2021) showed that cooked low glycemic rice (LGR) had significantly lower hardness, gumminess, chewiness, springiness, cohesiveness, and higher adhesiveness when compared with cooked native rice. These findings are different when compared with cooked brown rice varieties in Malaysia (Chapagai *et al*., 2020), which were reported to have lower hardness, cohesiveness, and adhesiveness values, as presented in Table 4. The possible cause for this variation could be attributed to differences in internal structures, amylopectin chains, gelatinization degree, ingredient mix, and processing conditions. In addition, research conducted by Karthik *et al*. (2024) showed that the Kodo millet extruded rice analogue had significantly lower hardness, adhesiveness, and cohesiveness, while higher chewiness and springiness when compared with cooked native rice. Thus, it can be disclosed that the formulation's variation and ratio caused different effects on the textural properties. Anindita *et al*. (2020) stated that the texture of extruded rice analogues became softer and less compact with the addition of soy flour. The presence of a substantial amount of protein in the food might lead to the formation of pores in its structure when subjected to high temperatures, such as during the hot extrusion process. This technique is believed to induce the expansion and aeration of the structure of the extruded rice analogues, thereby decreasing its hardness and cohesiveness. Furthermore, the reduction in hardness values can be attributed to the direct disruption of the starch network by soybean protein, resulting in a decrease in the rigidity of the starch network (Anindita *et al*., 2020).

Ramadhan *et al*. (2024) showed that in the seaweed-based extruded rice analogues, the product's hardness depended on the microwave power levels values. The optimal microwave cooking conditions produce specific texture characteristics and water absorption. By the ideal preferences for rice quality, panelists' favored sensory attributes for the extruded rice analogues were chewy and soft texture, dairy smell, grainy flavor, and moistness of grain appearance. According to their report, the cohesiveness value was influenced by extrusion parameters, material composition, moisture content, and cooking temperature. Furthermore, increased cooking power levels can negatively impact the interactions between amylose and amylopectin, increasing rice grains' stickiness. Similarly, Liu *et al*. (2022) studied the texture profile of cassava-based extruded rice analogues. The extruded rice analogues showed lower adhesiveness values and less stickiness than native rice. Nevertheless, the springiness, chewiness, and cohesiveness exhibited no significant differences comparable to the native polished rice. Sutrisno *et al*. (2024) stated that adding transglutaminase (TG) significantly improved chewiness by enhancing the protein network, making the texture firmer and more cohesive, and also improving springiness. TG maintains a good balance of elasticity and firmness. Increasing corn starch and TG levels in the recipe significantly increased hardness (Sutrisno et al. (2024), due to the fact that TG improves protein cross-linking, strengthening the texture of cooked extruded rice analogues.

Cooking behavior of extruded rice analogues

Extruded rice analogues cooking quality and sensory qualities mainly determine the acceptability of extruded rice equivalent at the consumer level. Typically, the cooking properties of extruded food products are measured by their swelling power (SP), cooking time (CT), cooking loss (CL), water absorption index (WAI), and water solubility index (WSI). Additionally, these cooking characteristics rely on starch gelatinization, retrogradation, and the speed at which water is absorbed or causes swelling (Dalbhagat *et al*., 2019).

The cooking time refers to the time needed to cook the rice thoroughly. Consumers have a preference for ready-to-cook convenient products. Hence, the cooking time of extruded rice analogues should be shorter than that of native rice. Furthermore, the extrusion method and various extrusion parameters substantially impact the cooking time of extruded rice analogues.

Table 5 shows the cooking behavior of extruded rice analogues as reported in the studied scientific literature.

Swelling power indicates how well starch hydrates in water and heat during cooking (Olu-Owolabi *et al*., 2011). Extruded rice analogues with a high swelling power suggest they can absorb water rapidly and need less cooking time. Ariyantoro *et al*. (2021) showed that the swelling power of extruded rice analogues made using purple sweet potato flour and 15% of Bambara groundnut flour was 8.99%. This value was higher than the commercial purple sweet potato extruded rice analogues analyzed in the study (8.75%), while cooking time was shorter - 11.54 min *vs*. 14.43 min.

High levels of amylose will enhance the swelling power, while lower levels will have the opposite effect. Polysaccharide molecules with high amylose content exhibit a greater capacity to absorb water and expand when compared to those with high amylopectin levels. The breakdown of weak hydrogen bonds in the amorphous region of amylose allows water absorption until it achieves its maximal hydration capacity. Similar findings were shown by Rumitasari *et al*. (2022), who obtained extruded rice analogues using white corn and mung bean flour, resulting in a high swelling power of 8.10-15.20 %. This is because white corn flour and mung beans have higher starch and fiber content, making them easier to cook. In addition, Mahendradatta *et al*. (2024) explained that the high starch and amylose content found in the ingredient (cassava) affects the swelling power. Amylose, characterized by its amorphous areas, exhibits reactivity towards water molecules, resulting in increased water absorption and enhanced swelling power of the starch.

Kharisma *et al*. (2014) demonstrated that the cooking time of extruded rice analogues produced using cassava, sago, and coconut pulp ranged from 3.5 to 5.5 min in comparison to native polished rice, which needed 14min to cook. The study found that the extrusion process caused partial gelatinization of extruded rice analogues, resulting in a shorter cooking time. In addition, Patria *et al*. (2020) found that as the temperature of the dough increases, the cooking time decreases due to the occurrence of starch gelatinization prior to cooking, so the cooking time in their study was shorter (4 min) compared to native rice (10.5 min). In a recent study conducted by Ramadhan *et al*. (2024), the researchers highlighted the advantageous effect of microwave cooking on the accelerated cooking process (5 min) and the overall physical, chemical, and sensory attributes of extruded rice analogues made from seaweed. Thomas *et al*. (2013) determined that the cooking time of local Malaysian native rice (white, brown, and Bario rice) was 10, 31.67, and 12.67 minutes, respectively. Thus, it can be concluded that overall, extruded rice analogues (Table 5) have shorter cooking times than different types of native rice.

According to Ramadhan *et al*. (2024), cooking loss is a crucial factor impacting extruded rice analogues' overall efficiency and energy consumption. It shows the decomposition of the product or its solid constituents during cooking. The occurrence of starch solubility during the cooking process of ERA increases cooking loss values. This situation would produce turbid boiled water or rice that has low cooking tolerance and is sticky when consumed (Yogeshwari *et al*., 2018). Patria *et al*. (2020) conducted research by using white rice Japonica Tainan 11 variety (TN-11), xanthan gum, emulsifier, and shortening, and found that increasing water content in the extruded rice analogues reduces the cooking loss value. This is because elevated moisture content may cause over-gelatinization of starch, resulting in a less cohesive matrix that is more prone to leaching during cooking (Zhang *et al*., 2020). Higher temperatures result in lower cooking loss and shorter cooking time for extruded rice analogues. Elevated temperature promotes starch gelatinization and protein denaturation, leading to a more cohesive and less soluble matrix that reduces the leaching of solids during cooking (Zhang *et al*., 2020). Extruded rice products processed at higher temperatures require less cooking time due to the pre-gelatinization of starch during extrusion process (Patria *et al*., 2020) (Table 5).

In their study, Yadav *et al*. (2021) showed that adjusting extrusion factors, such as the die heat temperature, can affect the cooking loss. Specifically, increasing the barrel temperature resulted in a higher cooking loss. Additionally, they stated that the combined influence of feed moisture and die temperature can decrease the cooking loss in composite flour-based extruded rice analogues.

Table 5. Cooking behavior of extruded rice analogues.

* SP (%)	WAI (g/g)	WSI (%)	BD (g/mL)	CT (min)	CL (%)	Observations	References
Extruded rice analogues - ingredients							
Cassava, sago, and coconut pulp							
-	6.9-8.35	6.69-9.55	0.50-0.54	3.5-5.5	3.32-3.36	The extrusion process resulted in partial gelatinization of extruded rice analogues, reducing cooking time compared to polished rice. The use of coconut pulp elevated both the WAI and WSI.	(Kharisma *et al.*, 2014)
Purple Sweet Potato Flour and 15% of Bambara Groundnut Flour							
8.99	175.50	23.45	0.57	11.54	-	Starch with high amylose content increased SP. Extruded rice analogues have short cooking times due to high water absorption.	(Ariyantoro *et al.*, 2021)
Broken rice with purple sweet potato powder							
-	5.71	9.68	-	-	-	The extrusion method promotes the breakdown of starch due to the elevated temperature and pressure. As the degree of degradation of starch increases, the size of the molecular sugars and dextrins decreases while the content of small molecular components increases, which leads to higher WSI and WAI values after extrusion and recombination.	(Wang *et al.*, 2021)
White Rice Japonica Tainan 11: TN-11, xanthan gum, emulsifier, and shortening							
-	2.27	2.11	-	4.00	1.92	Increasing water content leads to an increased WAI, WSI, extended cooking duration, and a reduced cooking loss value. Increasing the temperature led to lower cooking loss and shortened cooking time.	(Patria *et al.*, 2020)

Cassava flour: 50% corn + 50% lablab bean flour: soy flour							
-	118.00	-	0.51	11.00	12.08	The feed's temperature, residence time, and moisture content influenced extruded products' bulk density and porosity. Increased gelatinization temperature would result in a longer cooking time for extruded rice analogues	(Sukamto and Patria, 2020)
Sago flour, mung bean flour, corn flour							
-	-	-	0.49-0.65	29-35	-	Cooking rice resulted in its expansion, rise in volume but a drop in mass, resulting in a reduced bulk density. Rice analogue exhibits a significant level of porosity, influenced mainly by its nutritional composition and the method used for drying.	(Sumardiono *et al.*, 2021)
White corn and mung bean flour							
8.10-15.20	33.30-63.90	-	0.57-0.68	3.17-3.23	-	White corn flour and mung beans have a greater concentration of starch and fiber, facilitating quick cooking. The increase of mung bean flour produced higher water absorption.	(Rumitasari *et al.*, 2022)
Cassava flour, banana flour, Katuk leaf powder, soy lecithin							
31.64	77.27	-	0.55	14.07	-	Soy lecithin, as a stabilizer, can absorb water and enhance the water absorption of extruded rice analogues. Extruded rice analogues with low bulk density have high porosity. As the porosity of the extruded rice analogues increases, their ability to absorb water also increases.	(Mahendradatta *et al.*, 2024)
Soybean flour and corn starch and transglutaminase (TGase)							
-	205.88 - 182.42	-	-	-	10.15-8.03	The addition of 1% TGase reduced water absorption while significantly preventing and reducing cooking loss	(Sutrisno *et al.*, 2024)
Sago flour, rice flour, corn flour							
-	1.26-0.63	-	-	5.00-7.00	-	Microwave cooking demonstrated high efficacy in creating extruded rice analogues with nutritional value comparable to traditional methods. The optimal microwave cooking conditions were achieved at 270 W for 7 minutes.	(Ramadhan *et al.*, 2024)

SP - Swelling power; WAI - Water absorption Index; WSI - Water Solubility Index; BD - Bulk Density; CT - Cooking time; CL - Cooking loss

The Water Absorption Index (WAI) measures a substance's ability to absorb a certain quantity of water. The degree of cooking of extruded products can be determined using WAI as a functional indicator. According to Patria *et al*. (2020), raising the temperature decreases the water absorption index (WAI), whereas increasing the water content of the extruded rice analogues leads to a higher WAI. The extrusion method results in a noticeable increase in the amount of starch that undergoes gelatinization. Increasing temperature and pressure will result in an increased rate of starch dextrinization. Dextrinized starch facilitates water absorption. The WAI of a product is influenced by several elements, such as the type of extruder, the moisture content of the feed water, the rate at which the feed is supplied, the speed of the screw, the temperature of the last barrel, the arrangement of the screw, the compression ratio of the screw, and the size of the die. Water is an essential plasticizer in the extrusion process. It contributes to reducing the deterioration of rice starch and improves the extrudate's water absorption capacity. Higher screw speed and moisture levels can lead to an increase in water absorption index (WAI) in rice (Liu *et al*., 2011). Research conducted by Rumitasari *et al*. (2022) found that the water absorption index increased by adding mung bean flour due to its high starch content, which results in more water absorption. Additionally, the fiber content in these materials has a high capacity to absorb water because of the large size of the polymer and the presence of several hydroxyl groups. This allows it to retain higher amounts of water. Mahendradatta *et al*. (2024) explained that the high starch content of the ingredients used in the formulation (amylose content) had a notable impact on water absorption due to an amorphous region. In addition, soy lecithin, functioning as a stabilizer, absorbs water and improves the water absorption of extruded rice analogues. The hydrophilic properties of soy lecithin facilitate the fast binding of water from the surrounding air. According to Ariyantoro *et al*. (2021), extruded rice analogues with high water absorption will result in a shorter cooking time. This is because absorbing water would be intensive as its increased heating temperature of gelatinization increases the value of extruded rice analogues cooking time.

The water solubility index (WSI) indicates starch degradation during extrusion (Minweyelet *et al*., 2021). WSI quantifies the amount of polysaccharides discharged from a granule when an excessive amount of water is added. Gelatinization will proceed after starch repair, leading to the breakdown of amylose and amylopectin into smaller molecules. This deterioration occurs when materials are extruded under high temperature and pressure conditions. These comparatively little molecules exhibit a higher propensity for dissolution in water (Patria *et al*., 2020). The rise in WSI value is believed to result from the breakdown of the amylopectin and amylose chains during the extrusion process, leading to an increase in the overall amount of dissolved solids (Sandrin *et al*., 2018). Kharisma *et al*. (2014) found that increasing coconut pulp concentration increased WSI. It was probably because extruded rice analogues contained more soluble dietary fiber than insoluble dietary fiber, which was easier to break down. In addition, Wang *et al*. (2021) mentioned that the higher the degree of starch degradation, the smaller the molecular sugars and dextrins, and the higher the small molecular components' content, which led to higher WSI values after extrusion and recombination. According to Yogeshwari *et al*. (2018), a high solubility is undesirable since it leads to starch solubility during the cooking process of this particular type of rice, resulting in increased cooking loss. This scenario would result in the formation of cloudy boiled water or rice that has a low cooking tolerance and is sticky when consumed.

The nutritional value of extruded rice analogues

Recent studies have demonstrated that extruded rice analogues have the potential to provide good health impacts due to their high dietary fiber, resistant starch, and relatively low glycemic index. These products have the most significant benefits for patients with diabetes. Table 6 shows the nutritional composition of some extruded rice analogues as reported in the cited literature.

Low glycemic index (GI) foods are recommended for individuals with diabetes mellitus as part of their functional illness treatment. These types of food can be made from materials containing high levels of amylose and/or dietary fiber utilizing specialized processing techniques that enhance their resistant starch content. The extrusion method for extruded rice analogues combines high pressure, temperature, mechanical friction, and moisture to partially gelatinize materials. This combination of forces results in rapid cutting and brings physical and chemical transformations. The extruded product is subsequently dried to facilitate starch retrogradation, enhancing the resistance starch content (Mishra *et al*., 2012). The study conducted by Nugraheni *et al*. (2021) found that extruded rice analogues made from the combination of white Ipomea batatas, modified white Ipomea batatas, germinated Vigna radiata flour, germinated white zea mays flour, and Sago starch had significantly higher dietary fiber and resistant starch contents in comparison to native rice (22.11% and 3.43% *vs.* 3.28% and 1.69% respectively). Wang *et al*. (2021) found that the amylose content of purple sweet potato extruded rice analogues (ERPSP) was higher compared to the native rice (15.6 *vs*.13.55%). Similarly, the resistant starch content was higher (29.13%) in ERPSP compared to native rice (7.37%). Consequently, the glycemic index value of ERPSP was lower compared to native rice (79.11% vs. 91.52%). This could be attributed to the presence of anthocyanin in the purple sweet potato powder. The hypoglycemic effect of anthocyanins and anthocyanin-rich food is attributed to purple sweet potatoes' high resistant starch (RS) content. RS is less readily digested than native cereal starch, producing a specific hypoglycemic effect.

Avaro *et al*. (2009) categorized the amylose content as low (15%-22%), intermediate (23%-26%), high (27%-30%), and very high (>30%). Based on this standard, the extruded rice analogues made from sago starch and red bean flour resulted in an amylose content of 30.62-26.94% categorized as very high amylose content (Wahjuningsih *et al*., 2016). Nugraheni *et al*. (2022) made extruded rice analogues from cassava flour, modified cassava, germinated soybean flour, germinated sorghum flour, and sago starch, which resulted in a low amylose content of 16.60-16.98%. Meanwhile, Wahjuningsih and Susanti (2018) produced extruded rice analogues from Mocaf: arrowroot: red bean flour with an intermediate level of amylose content 24.91 (Table 6).

Extruded rice analogues containing moderate to high amounts of amylose are considered more beneficial for health, as they can help regulate the development of type 2 diabetes and obesity. This is because high amylose content in food leads to a delayed breakdown of glucose by amylase. A more significant amount of amylose in rice has been scientifically demonstrated to decelerate the process of starch digestion into glucose. This is attributed to the rice's resistance to amylase hydrolysis (Syahariza *et al*., 2013). The effect of amylose and resistant starch (RS) in lowering the GI is significant. Low carbohydrate content affects low GI levels (Table 6). Food with low carbohydrate content diminishes glycemic load, leading to a more gradual increase in blood glucose levels post-consumption (Eleazu, 2016)

The food's low glycemic index (GI) means a slower release of glucose, which results from higher resistant starch (RS) levels, or lower starch content altogether. Extruded rice analogues with higher resistant starch (RS) content are digested at a slower rate, leading to a slower release of glucose. As a result, extruded rice analogues have a lower glycemic index (GI) and trigger a lower insulin response compared to foods with low RS content (Kumar *et al*., 2018). Similarly, Damat *et al*. (2021) stated that food products with high levels of resistant starch (RS) exhibit both a hypoglycemic effect and a low glycemic index.

Table 6. Nutritional value of extruded rice analogues.

* A (%)	GI	TDF (%)	RS (%)	P (%)	C (%)	References
Rice						
White rice						
27.71	61	7.07	-	5.96	80.14	(Thomas *et al*., 2013; Osman *et al*., 2021)
Brown rice						
3.36	60	8.37	-	6.48	78.21	(Thomas *et al*., 2013; Osman et al., 2021)
Parboiled rice						
19.35	43-48	10.4-11.7	6.1-7.2	6.29	74.74	(Kumar and Prasad, 2018; Thennakoon and Ekanayake, 2022)
Extruded rice analogues - ingredients						
Corn, sorghum and Arenga starch						
-	47.09	5.22	-	-	-	(Budijanto *et al*., 2018)
Corn and Arenga starch						
-	52.31	5.18	-	-	-	(Budijanto *et al*., 2018)
Arrowroot flour and Black-eyed pea flour						
-	39.40 – 37.12	17.33 - 21.30	-	-	77.32-81.30	(Pricilla and Hakim Nata Buana, 2020)
Sago starch and read bean flour						
30.62-26.94	48.30-76.5	4.18-9.08	11.80-9.28	-	85.82-93.92	(Wahjuningsih *et al*., 2016)

* A (%)	GI	TDF (%)	RS (%)	P (%)	C (%)	References
Mocaf: Arrowroot: Red bean flour (80:10:10)						
24.91	-	7.04	6.71	6.17	89.88	(Wahjuningsih and Susanti, 2018)
Corn starch, modified cassava flour, natural arrowroot starch, modified arrowroot starch						
-	56.79-76.03	-	3.92-16.71	0.13-0.21	86.04-89.36	(Damat *et al*., 2021)
Cassava flour, modified cassava, germinated soybean flour, germinated sorghum flour, and sago starch						
16.60	40.19	19.64	3.43	7.78	68.91	(Nugraheni *et al*., 2022)
Arrowroot flour, germinated red kidney bean flour, germinated white sorghum flour, and sago starch						
18.25	-	19.81	3.43	8.07	68.74	(Nugraheni *et al*., 2020)
Broken rice with purple sweet potato powder						
15.60	79.11	2.94	29.13	8.07	-	(Wang *et al*., 2021)

A – Amylose; GI - Glycemic Index; TDI - Total dietary fiber; RS - Resistant starch content; P – Protein; C - Carbohydrate

Food can be regarded as a source of fiber if it contains ≥3 g dietary fiber per 100 g and as a high-fiber food if it contains ≥6 g per 100g (FAO and WHO, 2013). Based on this standard, the extruded rice analogues could be considered at least a source of dietary fiber (Table 6). The relationship between dietary fiber and the reduction of GI values is believed to be associated with the physiological function of its components. The constituents of dietary fiber can be classified as either soluble or insoluble fibers or as fermentable or unfermentable fibers. Insoluble dietary fiber primarily aims to mitigate disorders associated with the gastrointestinal system. The primary role of soluble dietary fiber is to inhibit the speed of digestion in the intestine, resulting in extended feelings of fullness and a reduced rate of increase in blood glucose levels (Nugraheni *et al*., 2022). Consequently, insulin is required to facilitate the transport of glucose into the body's cells and convert it into a less energetic form (Nugraheni *et al*., 2022). The protein level of extruded rice analogues can also influence their glycemic index (GI) value (Budijanto *et al*., 2018). The protein-amylose matrix increases the viscosity and structural complexity of the food. High viscosity slows food movement from the stomach to the small intestine, delaying gastric emptying. Slower gastric emptying rates are associated with prolonged digestion times and a more gradual release of glucose into the bloodstream. Protein-amylose matrix also hinders the access of α-amylase and other digestive enzymes to their substrates. This physical barrier reduces the rate and extent of starch digestion, leading to lower postprandial glucose levels (Li *et al*., 2021).

The presence of protein in food can create a food matrix containing amylose. In addition to enhancing protein levels, incorporating beans with other components in extruded rice analogues formulation also lowers the glycemic index (GI) (Budijanto *et al*., 2018). Palupi *et al*. (2023) stated that adding 40% kidney bean flour to extruded products lowered the glycaemic index (GI) value by 53.1% and enhanced the protein and fiber contents of the product by up to 8% and 6%, respectively. Gularte *et al*. (2012) found that adding bean flour in food products can decrease the glycemic index (GI) value by 18%. In addition, Supparmaniam et al. (2019) stated that raising the quantities of food fiber derived from starch lowered the product's glycemic index.

According to Gourineni *et al*. (2019), foods can be categorized as low GI (≤55), medium GI (56–69), and high GI (≥70), defining the glycemic index of a food by determining how much it elevates blood glucose compared to an identical weight of glucose. Malaysian native rice belongs to the medium glycaemic index (GI) category (white rice 61, Brown rice 60, and Bario rice 60.9-62.2) (Osman *et al*., 2021) The majority of the extruded rice analogues listed in Table 6 belonged to the category of low glycaemic index. Extruded rice analogues with low glycaemic index cause a slow rise in blood sugar levels. Food with a low glycemic index (GI) undergoes a slow digestion process, resulting in slower emptying from the abdomen. This leads to a delayed movement of food suspension (chyme) to the small intestine, leading to a slower glucose uptake in the small intestine. As a result, blood glucose changes are relatively small (Nugraheni *et al*., 2022). Similarly, Ratnaningsih *et al*. (2017) found that functional food products enhance satiety and promote colonic fermentation, thus slowing digestion and absorption of glucose.

Sensory properties of extruded rice analogues

The sensory quality of extruded rice analogues is significantly influenced by incorporating various ingredients and processing parameters. Several researchers have performed sensory evaluations on the created extruded rice analogues to assess their acceptability at a commercial level compared to native rice. Nugraheni *et al*. (2020) conducted a hedonic test of the developed sago starch, arrowroot flour, germinated red kidney bean flour, and germinated white sorghum flour extruded rice analogues. The panellists assigned a rating of greater than 5 out of 9 to each criterias, including aroma (5.90), color (5.93), texture (6.17), taste (5.93), and overall acceptance (6.67). This indicates that extruded rice analogues can be considered acceptable substitutes for native rice. Similarly, the results of a hedonic test study conducted by Ariyantoro *et al*. (2021), who used purple sweet potato flour and Bambara groundnut flour as raw materials, indicated that the acceptability of panelists also had a value of >5 out of 9, except in aroma (4.64) and texture (4.88). The same authors stated that the amount of Bambara groundnut flour increases, the aroma of extruded rice analogue falls due to the disagreeable aroma of Bambara groundnut. Consequently, as the levels rised, the overall acceptability experiences a substantial decrease.

Quispe *et al*. (2024) reported that the acceptability of extruded rice analogues made from canihua and rice flours was rather good, with a value of 4.07 out of 5, demonstrating the feasibility of obtaining an acceptable product. Similarly, Kamsiati *et al*. (2022) showed that the extruded rice analogues made using 90% banana, 10%

tapioca, and 0.5% GMS had an overall acceptability of 3.33 out of 5.00. Damat *et al*. (2022) reported that the developed extruded rice analogues with arrowroot starch, seaweed and spices had the overall acceptability scores from 3.2 to 4.0 out of 7.0, indicating that it was slightly acceptable. The panellists stated that the extruded rice analogues were slightly tasty, chewy, with uniform grain, and had a flavorful aroma. Therefore, accurately optimizing ingredient concentrations, extrusion, and cooking conditions is essential for creating palatable extruded rice analogues with appropriate nutritional qualities for consumers.

The opportunities and challenges of extruded rice analogues in the market

The extruded rice analogues demonstrate their potential as food products with rich dietary fiber, resistant starch, protein, and low glycemic index (helpful for diabetic diets) compared to native rice (as indicated in Table 6). Extruded rice analogues remain relatively unknown and lack public demand due to insufficient product introduction and education. This product still has weaknesses in its sensory attributes, particularly its color and aroma, which are less appealing than native rice. These factors result in an uncertain sales rate and make it challenging to maximize sales volume (Tain *et al*., 2023). Several studies have been conducted to develop a marketing strategy for extruded rice analogues to promote its consumption in the community. Research has demonstrated that the most effective marketing approach was to prioritize preserving the quality and functionality of the product, as this offers health advantages and significant nutritional value. Additionally, it is recommended that promotional efforts be intensified, the distribution network expanded, and the adult market segment (specifically individuals aged 30-40) be targeted at a certain income level. Although extruded rice analogues may be more expensive than regular rice, it is more nutritious and can fulfil nutritional needs without additional side dishes (Valencia and Purwanto, 2020).

According to Budijanto and Yuliana (2015), implementing the "academic, business, government, and community" paradigm can lead to a prosperous extruded rice analogues industry and effective marketing. Successful implementation of research discoveries in the food sector necessitates synergistic interaction among various stakeholders. The stakeholders should assume the following roles: higher education, researching rice analogues processing technology and functional qualities, and integrating on-farm and off-farm practices. Industry specializes in designing and engineering machinery such as extruders, and is involved in developing local commercial flour and related industries. Government: advocacy for the significance of consuming a wider variety of food. Farmers: cultivate crops to obtain raw materials in compliance with better agricultural principles.

Conclusions

The development of extruded rice analogues through hot extrusion processing represents a significant advancement in food technology, addressing global food security and offering functional and nutritious alternatives to native rice. Using locally sourced raw materials such as cassava, corn, sago, and legume flours, extruded rice analogues can provide healthier carbohydrates and meet consumer demands. Numerous studies have shown that extruded rice analgoues produced via extrusion offers better nutritional profiles, including low GI, high dietary fiber, and resistant starch, compared to native rice. Evaluating extruded rice analogues thermal, pasting, texture, cooking, nutritional, and sensory properties makes them a viable alternative for health-conscious and diabetic individuals. However, further investigation is needed to optimize sensory characteristics and ensure widespread acceptance by the general population. With their enhanced nutritional and functional properties, extruded rice analogues holds potential future food as part of food diversification to support the global food security and nutrition goals.

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