

# Formulation and Characterization of Analogue Rice from Rice, Arrowroot, and Porang Flours Using the Mixture Optimal Custom Design Method

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## Abstract

The increasing health concerns associated with the high glycemic index of white rice have encouraged the development of alternative staple foods. This study aimed to formulate and optimize an analogue rice using a composite of rice flour, arrowroot flour (*Maranta arundinacea*), and porang flour (*Amorphophallus muelleri*) using the Mixture Optimal Custom Design approach. The goal was to produce analogue rice with improved functional, physical, and nutritional properties. Fifteen formulations were generated and evaluated based on the water absorption index, water soluble index, swelling power, texture (hardness), and whiteness. The optimal formulation, comprising 58.1% rice flour, 39.3% arrowroot flour, and 2.6% porang flour, was identified using statistical modelling and confirmed through validation experiments. The optimized analogue rice demonstrated favorable hydration capacity, textural resilience, and high whiteness, which closely aligned with the quality benchmarks of conventional rice. Pasting behavior analysis revealed stable gelatinization and retrogradation properties suitable for household cooking applications. Notably, the product exhibited a significantly lower estimated glycemic index (40.93) than commercial analogue rice and conventional white rice, attributed to the glucomannan and resistant starch in porang flour. Comparative evaluation showed that this formulation outperformed the control and commercial samples across multiple quality indicators without compromising acceptability. These findings support the use of indigenous starch sources for developing functional analogue rice, contributing to dietary diversification, improved glycemic control, and local resource utilization. This study underscores the potential of optimized composite flours in addressing nutritional challenges and offers a scalable model for health-oriented staple food innovation.

**Keywords:** Analogue rice, Arrowroot flour, Porang flour, Rice flour, MOCD, Extrusion, eGI

## Introduction

Rice (*Oryza sativa* L.) has long been an important food staple, especially in Asia. It contributes more than half of the world's daily calories [1]. As the fourth-largest rice consumer globally, Indonesia has an annual consumption of approximately 35.3 million tons [2]. Despite its nutritional benefits, which include energy, carbohydrates, protein, and trace minerals, white rice has a relatively high glycemic index (GI), ranging from

54 to 94. This feature associates its consumption to higher postprandial blood glucose levels and a potentially increased risk of chronic diseases, such as type 2 diabetes mellitus [3]. In response to these health and nutritional challenges, innovations in functional staple food alternatives, particularly analogue rice, have gained attention. Analogue rice refers to rice-like granules made from non-rice sources through shaping

and texturizing processes, most commonly extrusion cooking. This innovation supports Indonesia's food diversification efforts, providing ways to utilize underused local resources and reduce reliance on traditional rice. Additionally, analogue rice formulas can be tailored to achieve specific nutritional and functional goals, such as a low glycemic index and increased fiber content [4,5].

Analogue rice can be manufactured wholly or partially with non-rice ingredients [6]. The production of analogue rice using non-rice ingredients offers greater flexibility in incorporating high-fiber or protein-rich components, whereas partly rice-based formulations have the advantage of improving acceptability by maintaining a familiar taste and texture closer to real rice [7]. Analogue rice can be made from any dietary product containing starch. Arrowroot (*Maranta arundinacea*) is another carbohydrate source that could be used as an alternative for analogue rice production. Arrowroot is a perennial plant with high starch content and significant commercial value [8]. Arrowroot flour contains up to 79.5% carbohydrate [9], which is equal to 78.9% in rice [9]. As a result, arrowroot flour will be employed as a substitute ingredient in rice analogues where rice flour is the main component. Rice flour is a processed rice product with 78% starch and 22% amylose [7].

Extrusion cooking, particularly single-screw extrusion, is widely utilized in the production of analogue rice due to its versatility, scalability, and ability to convert composite flours into rice-like granules with changeable density and texture. Gelatinization, starch melting, and shaping occur under regulated heat and pressure, influencing physicochemical characteristics and nutrient bioavailability [10]. Notably, glucomannan in porang flour has hydrocolloid behavior that might interact with gelatinized starch during extrusion, thereby affecting water-holding capacity, retrogradation, and end product texture [11].

Previous studies have explored various aspects of analogue rice production, focusing on how different flours, extrusion parameters, and functional additives influence product performance. Budijanto and Yuliana [4] investigated sorghum-based analogue rice and emphasized its potential for diversifying staple diets. Damat *et al.* [12] demonstrated that incorporating

arrowroot flour with seaweed or corn flour can produce acceptable analogue rice with low glycemic index (GI) values. In relation to porang flour, Patria *et al.* [13] reported that restructured rice fortified with porang glucomannan through extrusion exhibited improved physicochemical, microstructural, and nutritional properties, including a lower glycemic index, higher water absorption, and enhanced health benefits, making it a promising functional food alternative.

This research focuses on formulating and characterizing analogue rice made from rice, arrowroot, and porang flours using the Mixture Optimal Custom Design (MOCD) method. The study specifically examines how varying the proportions of these 3 flours affects key physical properties, including water absorption index (WAI), water solubility index (WSI), swelling power, hardness, and whiteness. The MOCD approach is employed to determine an optimal formulation that balances these factors. The selected formulation is then evaluated and compared with commercial analog rice and regular white rice to assess improvements in functionality, cooking performance, and glycemic response.

In summary, this study aims to analyze the relationship between flour composition and the physicochemical properties of analogue rice. To the best of our knowledge, no previous research has explored the combined use of rice, arrowroot, and porang flours in a single formulation. Furthermore, the application of the Mixture Optimal Custom Design (MOCD) method for optimizing analogue rice formulations remains underreported. The findings of this study are expected to provide valuable insights for future research and development in functional food formulation, particularly for extrusion-based rice analogues. In addition, the study anticipates broader implications for small and medium-sized food enterprises seeking to commercialize nutritious and affordable rice alternatives.

## Materials and methods

### Materials

The primary ingredients used in this study were rice flour made from Sherpa rice, arrowroot flour (*Maranta arundinacea* L), and porang flour (*Amorphophallus muelleri* Blume), which contains 73.5% glucomannan. Sherpa rice variety was obtained

from Lee Mao International Pty., Ltd, while arrowroot flour was purchased under the Cap Burung brand. Porang flour was procured from a local supplier. Additional materials included food-grade calcium hydroxide, glycerol monostearate (GMS) from Nura Gemilang (Malang), white margarine (Wang Lai), and emulsifiers from online sources. The enzymatic reagents used in glycemic index (GI) determination included pepsin (P7000),  $\alpha$ -amylase (A3176), amyloglucosidase (A7095), and a glucose oxidase-peroxidase kit (GOPOD reagent) from Megazyme International Ltd., Ireland, alongside D-glucose standard.

### Experimental design

The optimization process was carried out by Mixture Optimal Custom Design (MOCD) using 3 center points. Fifteen experimental treatments were used to set up the experimental plan within  $-1$  to  $+1$  (coded levels) with variables of rice flour (56% - 80%), arrowroot flour (16% - 40%), and porang flour (1% - 4%). The responses used in this study were the water absorption index (WAI), water soluble index (WSI), whiteness, hardness, and swelling power. The optimized formulation of analogue rice will be further analysed for its chemical components, microstructure, water absorption ratio (WAR), cooking loss, cooking time, texture profiles, pasting behavior, and eGI at the most optimum treatment point.

### Rice analogue preparation

Analogue rice was prepared following the modified protocols of Patria *et al.* [13]. Initially, the Sherpa variety of white rice was milled using a small grinder (RT-04, Mill Powder Tech Co., Ltd., Taiwan) and subsequently sieved through an 80-mesh filter using sieve shakers (AS 200, RETSCH Ltd., Germany). Rice flour, arrowroot flour, and porang flour were added based on the results of the setup from the design expert software (w/b, total dough basis), and an emulsifier (1%, w/b), shortening (2.5%, w/b), and xanthan gum (1%, w/b) were added based on the total dough. After the mixture was turned into a dough, it was placed on a pasta extrusion machine (La Monferrina Model P6, Roma, Italy) with a die shaped like rice ( $2.22 \times 8.69$  mm<sup>2</sup>), and the dough was cut into rice kernels. Then, the analogue rice was transferred to a dehydrator and dried at 40 °C for 2 h.

### Water Absorption Index (WAI) and Water Soluble Index (WSI)

The WAI and WSI of the analogue rice were determined using Eqs. (1) and (2), respectively, as outlined by Reshi *et al.* [14].

$$\text{WAI (g/g)} = \left[ \frac{\text{Weight of gel (g)}}{\text{Weight of sample flour (g)}} \right] \quad (1)$$

$$\text{WSI (\%)} = \left[ \frac{\text{Weight of dried supernatant (g)}}{\text{Weight of sample flour (g)}} \times 100\% \right] \quad (2)$$

The weight of the gel represents the residue remaining after the removal of the liquid portion, and the supernatant represents the liquid portion separated from the residue after centrifugation.

### Whiteness

The color of the analogue rice sample was determined based on the procedure described by Nielsen [15] using a colorimeter (Color Quest XE, Hunter Lab, Inc., USA). The results of the whiteness analysis are shown in the form of L, a, and b values. The total degree of color was measured using a white base. Therefore, whiteness can be calculated using Eq. (3).

$$W = [100 - \sqrt{(100 - L)^2 + a^2 + b^2}] \quad (3)$$

### Texture profile analysis

The texture profile analysis of the analogue rice was modified based on Wang *et al.* [16] using a Texture Profile Analyzer (5564, Instron Co., USA). The rice-shaped sample was compressed to 50% deformation. The plunger was withdrawn to the original height, and the sample was stopped for 5 s, followed by a compression-withdraw cycle at 50% deformation. The speed of the compression head was adjusted to 30 mm/min, and the diameter of the probe was 3.09 mm. The hardness value was defined as the maximum peak force during the first compression.

### Swelling power

The swelling power of the analogue rice was measured using the method described by Tao *et al.* [17] with some modifications. The rice analogue flour (1% w/v) in volume-calibrated sealed tubes was heated at 80 °C in a shaking water bath for 30 min, cooled for 5 min,

and centrifuged at 3,000×g for 15 min. The supernatant was separated, and the swollen starch sediment was weighed after centrifugation. The swelling power can be calculated using Eq. (4):

$$\text{Swelling power (g/g)} = \left[ \frac{\text{weight of sediment (g)}}{\text{dry weight of flour sample (g)}} \right] \quad (4)$$

### Proximate analysis

Proximate analysis of the nutritional composition was performed for water, ash, carbohydrate, crude fat, crude protein, and crude fiber using the method of the Association of Official Analytical Chemists [18].

### Rice analogue microstructure

The microstructure of the restructured rice was examined using a scanning electron microscope (SEM, S-3000N, Hitachi High Technologies Co., Japan) at 1,500× magnification.

### Water Absorption Ratio (WAR), cooking losses, and cooking time

The water absorption ratio and cooking losses during cooking were modified as described by Kang *et al.* [19]. The sample (5 g) was cooked in 20 mL of boiling distilled water for 2 - 4 min. After the completion of the cooking process, the leached solids were removed and placed in a petri dish for drying at 105 °C. Simultaneously, the weight of the cooked rice was measured accurately, and the WAR was calculated. The dried leached solids were weighed, and their cooking losses were noted. WAR and cooking losses were calculated using Eqs. (5) and (6), respectively.

$$\text{WAR (\%)} = \left[ \frac{B - A}{A} \times 100\% \right] \quad (5)$$

$$\text{Cooking Losses (\%)} = \left[ \frac{C}{A} \times 100\% \right] \quad (6)$$

Note that, A is the weight of dry rice (g), B is the weight of cooked rice (g), and C is the weight of dried supernatant (g).

The cooking time of the samples was estimated using the method described by Singh *et al.* [20].

### Pasting behavior

Pasting characteristics were assessed using a Rapid Visco Analyzer (RVA Starchmaster 2, Newport Scientific, Perkin Elmer) based on the protocol by Kraithong *et al.* [21]. The measured parameters included peak viscosity (PV), trough viscosity, breakdown, final viscosity, setback, and pasting temperature.

### *In vitro* starch digestibility and estimated glycemic index (eGI)

The rate of *in vitro* starch hydrolysis was analyzed using the method established by Goñi *et al.* [22]. A 50 mg sample was prepared, followed by the addition of 10 mL of HCl-KCl buffer (pH 1.5, adjusted). Subsequently, 0.2 mL of a solution containing 1 g of pepsin dissolved in 10 mL of HCl-KCl buffer was added to each sample, and the mixture was incubated at 40 °C for 1 h in a shaking water bath. The volume was then adjusted to 25 mL with Tris-Maleate buffer (pH 6.9). Next, 5 mL of an  $\alpha$ -amylase solution in Tris-Maleate buffer (containing 2.6 U) was added to each sample, which was subsequently incubated at 37 °C in a shaking water bath. Aliquots of 1 mL were collected from each tube every 30 min for a duration of 0 to 3 h. Each aliquot was transferred into a tube, heated at 100 °C for 5 min with vigorous shaking to inactivate the enzyme, and stored under refrigeration until the end of the incubation period. Thereafter, 3 mL of 0.4 M sodium acetate buffer (pH 4.75) were added to each aliquot, and 60  $\mu$ L of amyloglucosidase were introduced to hydrolyze the digested starch into glucose during a 45-minute incubation at 60 °C in a shaking water bath. The volume was adjusted to 10 - 100 mL with distilled water. Triplicate aliquots (0.5 mL each) were then incubated with Peridochrom Glucose GOD-PAP (Ref 676 543, Boehringer). Finally, the glucose content was converted to starch equivalent by multiplying by 0.9.

### Statistical analysis

Data analysis was performed using the Design Expert (DX) 13 program. The analysis results in the values of WAI, WSI, whiteness, hardness, and swelling power of each analogue rice obtained in the treatment. The results of making optimal and validated analogue rice were analyzed in terms of the chemical components, microstructure, texture profiles, cooking characteristics, pasting behavior, and *in vitro* glycemic index

evaluation. Subsequently, it was compared with milled rice and commercial analogue rice in the ANOVA statistics analysis using Minitab version 19 software.

**Results and discussion**

**Optimization of analogue rice**

The WAI values obtained ranged from 2.415 to 3.422 g/g. Model selection was determined based on a *p*-value of less than 0.05. The analysis indicated that the Sp quartic model versus the quadratic model was recommended by the Design-Expert (DX) 13 software (Table 1). As the proportion of arrowroot flour decreased, the proportion of rice flour increased. Rice flour, which is high in starch and amylopectin, provides a greater capacity for water absorption [23]. Amylopectin reacts with water, thereby enhancing the absorbency of rice. The presence of glucomannan in porang flour is believed to influence the WAI value. The hydrophilic properties and glucomannan’s water-holding capacity strengthen analogue rice’s ability to absorb water [24].

The data obtained from the WSI ranged from 0.815% to 1.696%. The model was determined based on a *p*-value of more than 5% (Table 1). The analysis results show that the DX 13 program recommends the cubic model (Table 1). Higher glucomannan levels raise the WSI value because glucomannan is a water-soluble

dietary fiber [13]. Arrowroot flour has sticky properties and forms a gel after heating, which causes a decrease in WSI [23]. Denatured proteins affect the WSI of rice analogues. During extrusion, the heat involved leads to protein denaturation [25]. Porang flour has a relatively high protein content of 9.50%, especially when compared to rice flour at 8% and Arrowroot flour at 0.7% [26]. Because the proportion of porang flour used was minimal and Arrowroot flour has a low protein content, the overall protein level in the rice analogue remained largely unchanged. Consequently, there was no significant variation in the amount of denatured protein across the different treatments.

The whiteness data ranged from 64.994 to 68.599. The model was determined based on a *p*-value of less than 5% (Table 1). The analysis results showed that the linear model was recommended by the DX 13 program (Table 1). The bright white color of arrowroot flour is believed to enhance the whiteness of analogue rice [27]. The higher the arrowroot flour content, the more dominant the white colour, thereby increasing the product’s whiteness value. Meanwhile, using more porang flour can lower the whiteness of the analogue rice because of its natural brown color [13]. As the proportion of porang flour increased, the whiteness of the product decreased.

**Table 1** Results of variance analysis on the characteristics of analogue rice.

Sources	Responds				
	WAI (g/g)	WSI (%)	Whiteness	Hardness (N)	Swelling power (g/g)
Model	<i>Sp Quartic vs Quadratic</i>	<i>Cubic</i>	<i>Linear</i>	<i>Cubic</i>	<i>Sp Quartic vs Quadratic</i>
	<i>p-value</i>				
Model	0.0027	0.1043	0.0275	0.0024	0.0071
<sup>(1)</sup> Linear Mixture	0.1383	0.3680	0.0275	0.0036	0.0037
TB*TG	0.0756	0.9363	-	0.2714	0.0040
TB*TP	0.0993	0.1224	-	0.0002	0.0207
TG*TP	0.8280	0.1196	-	0.0002	0.0195
TB*TG*TP	-	0.1196	-	0.0002	-
TB*TG(TB-TG)	-	0.0755	-	0.0011	-
TB*TP(TB-TP)	-	0.1257	-	0.0002	-
TG*TP(TG-TP)	-	0.1158	-	0.0002	-
TB <sup>2</sup> *TG*TP	0.416	-	-	-	0.0935
TB*TG <sup>2</sup> *TP	0.364	-	-	-	0.0046
TB*TG*TP <sup>2</sup>	0.2326	-	-	-	0.089

Sources	Responds				
	WAI (g/g)	WSI (%)	Whiteness	Hardness (N)	Swelling power (g/g)
<i>Lack of Fit</i>	0.5533	0.1217	0.8141	0.2849	0.0208
	Statistics				
Standard deviation	0.0997	0.1420	0.9536	0.7231	0.2849
Mean	3.0300	1.1900	66.5300	12.9600	7.7500
R <sup>2</sup>	0.9466	0.8536	0.4506	0.9714	0.9248
<i>Adeq Precision</i>	11.9760	6.2424	17.3120	7.1496	13.0819

Note: TB = Rice flour, TG = Arrowroot flour, TP = Porang flour

The obtained hardness values varied between 6.980 and 17.401 N. The model was established using a *p*-value of less than 5% (Table 1). The analysis results show that the cubic model is recommended by the DX 13 software (Table 1). The increase in hardness attributed to the addition of porang flour is thought to arise from its crosslinking with calcium ions. The incorporation of Ca(OH)<sub>2</sub> as an additive introduces calcium ions that can form bonds with the hydroxyl (OH) groups present in the glucomannan molecule. [13]. This results in robust connections that enhance the structural strength and resistance to deformation, thereby improving the hardness. Arrowroot flour is believed to alter the balance between amylose and amylopectin levels. Arrowroot flour-based rice substitutes tend to be firm or crunchy because they contain higher levels of amylose [23].

The swelling power ranged from 6.245 to 9.113 g/g. The model selection was based on a *p*-value of less than 5%. Analysis results indicated that the DX 13 program recommended the Sp quartic versus quadratic model (Table 1). Arrowroot starch possesses a granular structure that readily absorbs water [28]. As the proportion of arrowroot starch in the analogue rice

formulation increased, more starch granules became available to absorb water, thereby enhancing the product’s swelling capacity. Glucomannan, which has a high water-holding capacity, enables analogue rice containing porang flour to absorb more water during cooking [24]. When glucomannan absorbs water, its molecules expand and form a gel, increasing the volume and expansion ability of the rice analogue. In this formulation, arrowroot flour primarily contributes to swelling power because it is used in larger quantities compared to porang flour.

**Validation data of optimum conditions**

Validation was carried out by applying the optimum solution results from the program that was predicted in the production of analogue rice using factors such as rice, arrowroot, and porang flour, 58.10%, 39.33%, and 2.57%, respectively, with a desirability value of 0.778. Table 2 shows the prediction results from the optimum solution point of the water absorption index (WAI) of 2.988 g/g, water solubility index (WSI) of 1.239%, whiteness of 67.218%, hardness of 17.398 N, and swelling power of 8.395 g/g.

**Table 2** Verification test of optimization results.

	Variables			Responds				
	TB (%)	TG (%)	TP (%)	WAI (g/g)	WSI (%)	Whiteness	Hardness (N)	Swelling Power (g/g)
Predicted	58.100	39.326	2.575	2.988	1.239	67.218	17.399	8.395
Validation	58.100	39.326	2.575	2.994 ± 0.044	1.130 ± 0.093	67.217 ± 0.233	17.435 ± 0.251	8.391 ± 0.058
<i>p</i> -value				0.921	0.101	0.993	0.826	0.934
Desirability						0.778		

### Characterization and evaluation of optimum restructured rice

#### Chemical components

The carbohydrate content (**Table 3**) of the optimal analogue rice differed significantly ( $p < 0.05$ ) from the others. The carbohydrate level of the optimal rice analogue was 79.63%, which was lower than that of Sherpa rice (81.75%). Variations in the protein, fibre, and resistant starch content of each flour influence the total carbohydrate content of the rice analogue [29]. Rice flour contains approximately 8% protein [30]. Arrowroot flour contains 0.70 g of protein, 3.4 g of fibre, and 2.12% resistant starch per 100 g [8]. Porang flour contains 9.50% protein and 4.16% starch [26]. Mixing

the 3 flours is believed to alter the composition of other nutrients, thereby influencing the total carbohydrate content of the analogue rice. When this mixing process is combined with heat treatment (such as during extrusion cooking), it can induce chemical reactions, including the Maillard reaction - a condensation reaction between sugars and amino acids - which may reduce the measurable availability of carbohydrates [31]. Additionally, the analogue rice production process is thought to affect the carbohydrate content of the final product. The study by Bernas *et al.* [32] showed similar results, with analogue rice having a lower carbohydrate content than white rice

**Table 3** Chemical composition of optimal formulation analogue rice compared to other rice products.

No.	Parameter (%)	Optimal analogue rice	Analogue rice without Porang	“Fukumi” analogue rice (Indonesia)	Sherpa rice (Taiwan)
1	Carbohydrates	79.63 ± 0.060 <sup>c</sup>	75.21 ± 0.196 <sup>d</sup>	82.30 ± 0.102 <sup>a</sup>	81.75 ± 0.328 <sup>b</sup>
2	Crude protein	6.92 ± 0.062 <sup>c</sup>	6.68 ± 0.026 <sup>d</sup>	7.36 ± 0.053 <sup>b</sup>	7.61 ± 0.101 <sup>a</sup>
3	Crude fat	2.98 ± 0.113 <sup>a</sup>	1.48 ± 0.068 <sup>b</sup>	0.12 ± 0.020 <sup>c</sup>	1.59 ± 0.210 <sup>b</sup>
4	Ash content	0.54 ± 0.011 <sup>ab</sup>	0.51 ± 0.045 <sup>ab</sup>	0.57 ± 0.057 <sup>a</sup>	0.48 ± 0.037 <sup>b</sup>
5	Moisture content	9.93 ± 0.110 <sup>b</sup>	16.13 ± 0.126 <sup>a</sup>	9.65 ± 0.035 <sup>b</sup>	8.58 ± 0.406 <sup>c</sup>
6	Crude Fiber	12.41 ± 1.612 <sup>b</sup>	16.51 ± 0.465 <sup>a</sup>	16.32 ± 0.192 <sup>a</sup>	11.86 ± 1.529 <sup>b</sup>

\* Each sample was tested in triplicate. Different notations on the same line indicate significant differences at  $\alpha = 0.05$  (5%).

The crude protein content (**Table 3**) of the optimal analogue rice significantly differed ( $p < 0.05$ ) from that of the others. The highest crude protein content (7.61%) was observed in Sherpa rice, which is used as a raw material for rice flour in this research. The low protein levels in analogue rice are due to protein denaturation [33]. When proteins in rice analogues undergo denaturation, heat or mechanical processing (such as extrusion) disrupts amino acid bonds (except for primary peptide bonds), causing protein unfolding and aggregation [34]. This process leads to a reduction in the measurable total protein content of the rice analogue. Consequently, the total crude protein content of the optimal formula, the “Fukumi” analogue rice, and the analogue rice without porang was lower than that of Sherpa rice.

The crude fat content of the optimal analogue rice (**Table 3**) was significantly different ( $p < 0.05$ ) from that

of the other samples. The fat content in the optimal analogue rice was 2.98%, which was higher than that found in Sherpa rice (1.59%), “Fukumi” analogue rice (0.12%), and analogue rice without porang (1.48%). This is believed to be due to other additives, such as shortening. Adding shortening to the analogue rice dough is thought to increase its fat content [13]. The presence of fat in analogue rice aids in rice shaping and softens the texture [23].

The ash content (**Table 3**) of the optimal analogue rice showed no significant difference ( $p > 0.05$ ) from the others. The ash content of the optimal analogue rice was 0.54%, which was higher than that of Sherpa rice (0.48%). The ash content of food is often linked to the mineral levels in raw materials [35]. The high ash content of the analogue rice is probably due to the diverse mineral content of arrowroot and porang flours. Arrowroot flour contains essential minerals for the

body, including 454 mg of potassium, 28 mg of calcium, 22 mg of phosphorus, and 1.7 mg of iron per 100 g [23]. Porang flour contains approximately 2.60% - 3.84% ash content [36].

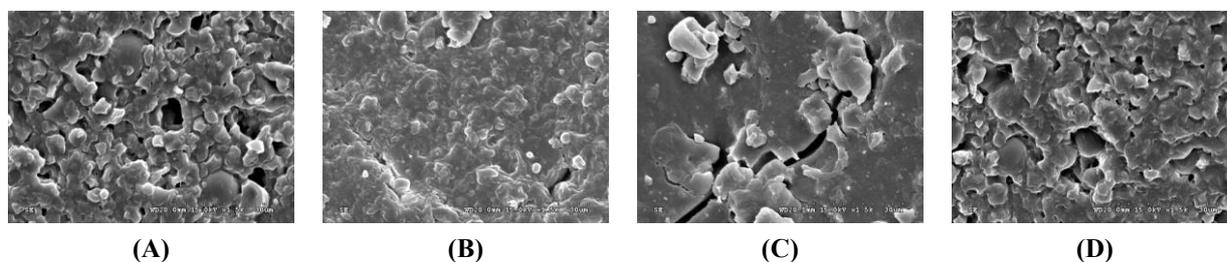
The moisture content of the optimal analogue rice (**Table 3**) was significantly different from that of the other samples ( $p < 0.05$ ), measuring 9.93%. It was also significantly higher than that of Sherpa rice (8.58%). This difference can be attributed to the unique starch structure of arrowroot flour, which, due to its relatively high amylose content, enhances the ability of rice analogues to absorb and retain water [37]. Amylose readily interacts with water through hydrogen bonding, making it an effective moisture binder [38]. Additionally, porang flour contributes to this effect through its glucomannan content, which is highly hydrophilic and strongly absorbs water during heating, further increasing the overall moisture content [39].

As shown in **Table 3**, the crude fiber content of the optimal analogue rice was significantly higher ( $p < 0.05$ ) than that of Sherpa rice, with values of 12.41% and 11.86%, respectively. This difference is primarily attributed to the incorporation of arrowroot flour, which is naturally rich in fiber, containing 4.61% insoluble

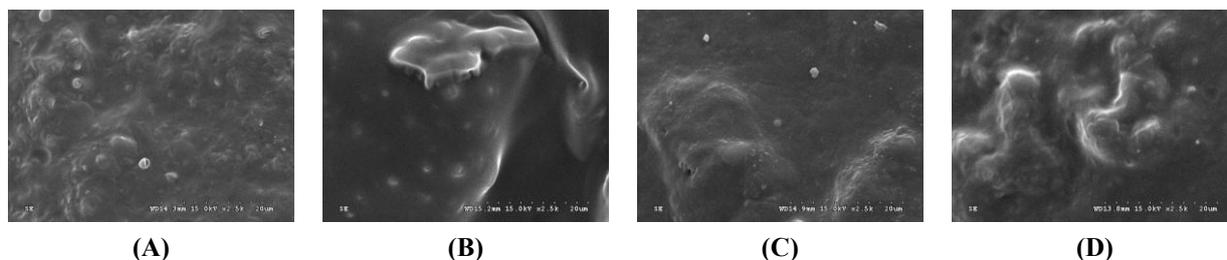
fiber and 2.08% soluble fiber [23]. Porang flour, although contributing less (around 0.79% crude fiber) [40]. Consequently, the analogue rice without porang had a higher crude fiber content than the “Fukumi” analogue rice, which incorporated porang. A high crude fiber content can slow the digestion process, create a longer feeling of fullness, and reduce the rise in blood glucose [41].

### Microstructure

As shown in **Figure 1**, the microstructure of the optimal analogue rice (A) was more porous than that of Sherpa rice from Taiwan (B). Processing methods such as extrusion are believed to affect the rice microstructure. While extrusion can produce analogue rice that looks like real rice, replicating its microstructure is more challenging [39]. The composition of raw materials for analogue rice, including hydrocolloids like glucomannan from porang flour and fiber from Arrowroot flour, is also believed to affect this. These hydrocolloids create a gel structure and matrix that are more porous (hollow) than the solid structure of natural rice grains [42].



**Figure 1** Microstructure of (A) the optimal formulation of analogue rice, (B) Sherpa rice (Taiwan), (C) “Fukumi” analogue rice (Indonesia), and (D) the optimal formulation of analogue rice without porang, observed before cooking at 1,500× magnification.



**Figure 2** Microstructure of (A) the optimal formulation of analogue rice, (B) Sherpa rice (Taiwan), (C) “Fukumi” analogue rice (Indonesia), and (D) the optimal formulation of analogue rice without porang, observed after cooking at 1,500× magnification.

The cooked optimal analogue rice (**Figure 2(A)**) resembles Sherpa rice (Taiwan) (**Figure 2(B)**). The optimal analogue rice (**Figure 2(A)**) appears to be well gelatinized. This can be observed from the microstructure of the cooked analogue rice (**Figure 2(A)**), which appeared denser or less porous. Hydrocolloids, such as glucomannan, are thought to affect the microstructure of analogue rice. The addition of glucomannan can create a gel network that binds water and starch molecules, resulting in rice with a uniform microstructure [39]. Proper cooking conditions can also achieve a uniform microstructure owing to optimal starch gelatinization [43].

### Texture profiles

Based on **Table 4**, the hardness of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the other comparison products. The hardness of the optimal analogue rice was 2.499 N, which was higher than that of Sherpa rice (Taiwan) at 0.327 N. Arrowroot flour has a hard texture owing to its high amylose content. Amylose contributes to this hardness because it undergoes gelatinization when heated, creating a dense and sturdy structure [12]. Porang flour containing glucomannan is also suspected of increasing hardness because glucomannan, as a thickening agent and gel former, can form a solid gel structure that enhances the final texture of analogue rice after cooking [44].

**Table 4** Results of texture analysis of cooked samples.

No	Parameters	Optimal Analogue Rice	Analogue Rice Without Porang	“Fukumi” Analogue Rice (Indonesia)	Sherpa Rice (Taiwan)
1	Hardness (N)	2.499 ± 2.52 <sup>a</sup>	1.065 ± 0.48 <sup>b</sup>	0.178 ± 0.15 <sup>b</sup>	0.327 ± 0.20 <sup>b</sup>
2	Gumminess (N)	0.342 ± 0.39 <sup>a</sup>	0.316 ± 0.27 <sup>a</sup>	0.083 ± 0.07 <sup>b</sup>	0.037 ± 0.03 <sup>b</sup>
3	Cohesiveness	0.810 ± 0.13 <sup>a</sup>	0.793 ± 0.12 <sup>a</sup>	0.858 ± 0.07 <sup>a</sup>	0.096 ± 0.11 <sup>b</sup>
4	Adhesiveness (J)	-0.001091 ± 0.000554 <sup>c</sup>	-0.000760 ± 0.000438 <sup>b</sup>	-0.000052 ± 0.000104 <sup>a</sup>	-0.000741 ± 0.000246 <sup>b</sup>
5	Chewiness (Nm)	0.103 ± 0.12 <sup>ab</sup>	0.164 ± 0.16 <sup>a</sup>	0.044 ± 0.04 <sup>bc</sup>	0.008 ± 0.01 <sup>c</sup>

\*Different notations on the same line indicate significant differences at  $\alpha = 0.05$  (5%).

According to **Table 4**, the gumminess parameter of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the other comparison products. The hardness of the optimal analogue rice was 0.342 N, which was higher than that of Sherpa rice (Taiwan) (0.037 N). Gumminess refers to the stickiness of rice when chewed [45]. The high glucomannan content of porang flour is believed to affect the gumminess value. Glucomannan functions as a thickening agent that can retain high water content, thereby increasing water absorption in analogue rice [36]. This results in rice grains that are denser, more cohesive, and stickier after cooking, ultimately increasing the hardness, cohesiveness, and gumminess.

**Table 4** shows that the cohesiveness of the optimal analogue rice was significantly higher ( $p < 0.05$ ) than that of the comparison products. The optimal analogue

rice exhibited a cohesiveness of 0.810, which was greater than the 0.096 cohesiveness of Sherpa rice from Taiwan. Cohesiveness indicates how effectively a product can retain its internal structure when subjected to pressure or compression [46]. Glucomannan plays a crucial role in the properties of analogue rice by forming a strong, viscous gel upon heating. This gel fortifies the connections between rice grains, allowing them to adhere more effectively [36]. In addition, the use of additives such as xanthan gum further enhances this effect by creating a stable gel network, ensuring that the rice retains its texture and shape throughout cooking [47].

As shown in **Table 4**, the adhesiveness of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the other comparison products. The optimal analogue rice exhibited an adhesiveness of

-0.001091 J, which was less than that of Sherpa rice from Taiwan (-0.000741 J). Adhesiveness measures the force required to separate 2 surfaces in contact. Adhesiveness indicates the likelihood of rice sticking to the eating utensils [48]. The high amylose content of arrowroot flour is believed to reduce adhesiveness. High amylose levels lead to firm and non-sticky rice when it is cooked [23]. Porang flour and its glucomannan form a gel with water. However, it creates a chewy texture and is not excessively sticky [49].

**Table 4** indicates that the chewiness of the optimal analogue rice differed significantly ( $p < 0.05$ ) from that of the comparison products. The optimal analogue rice achieved a chewiness value of 0.103 Nm, whereas Sherpa rice from Taiwan registered only 0.008 Nm. Chewiness measures the energy required to chew rice until it is ready to be swallowed, with higher values signifying a more elastic texture [50]. The enhanced chewiness was closely associated with the function of the porang flour. Its glucomannan content possesses an exceptional capacity to absorb and retain water, creating a gel when cooked [36]. Glucomannan can absorb water and form a gel, which helps make the final rice texture more elastic.

### Cooking characteristics

As shown in **Table 5**, the water absorption ratio (WAR) of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the other comparison products. The optimal WAR of the optimal analogue rice was 226.42%, which exceeded that of Sherpa rice (Taiwan) at 129.31%. The Water Absorption Ratio (WAR) measures the water absorption capacity during cooking. The water absorption capacity of flour is significantly influenced by its amylose and amylopectin contents. Amylose is easily soluble, and amylopectin interacts with water molecules, leading to increased water absorption in analog rice during cooking [23]. The results showed that the optimal analogue rice and analogue rice without porang exhibited higher WAR values than Sherpa rice (**Table 5**). Glucomannan is a substance capable of absorbing water up to 100 - 200 times its own weight. As a result, analogue rice made from porang flour (including both optimal analogue rice and "Fukumi" analogue rice) tends to absorb more water during cooking, as evidenced by a higher WAR compared to Sherpa rice (**Table 5**).

**Table 5** Results of the cooking characteristics analysis.

No	Parameter	Optimal Analogue Rice	Optimal Analogue Rice Without Porang	"Fukumi" Analogue Rice (Indonesia)	Sherpa Rice (Taiwan)
1	Water Absorption Ratio (%)	226.42 ± 3.993 <sup>a</sup>	197.00 ± 2.951 <sup>c</sup>	213.14 ± 7.730 <sup>b</sup>	129.31 ± 2.147 <sup>d</sup>
2	Cooking Losses (%)	8.35 ± 0.218 <sup>a</sup>	6.95 ± 0.061 <sup>b</sup>	3.41 ± 0.174 <sup>d</sup>	5.59 ± 0.093 <sup>c</sup>
3	Cooking Time (min)	30.69 ± 0.059 <sup>d</sup>	32.79 ± 0.025 <sup>c</sup>	34.39 ± 0.092 <sup>b</sup>	35.12 ± 0.092 <sup>a</sup>

\*Different notations on the same line indicate significant differences at  $\alpha = 0.05$  (5%).

Based on **Table 5**, cooking losses in optimal analogue rice were significantly ( $p < 0.05$ ) different from those of other comparison products. The cooking loss for optimal analogue rice was 8.35%, which was higher than that of Sherpa rice (Taiwan) at 5.59%. The extrusion process may have contributed to the higher cooking losses. In analogue rice, produced through extrusion, changes occur in the hydrogen bonds between starch molecules, making the matrix less stable for retaining ungelatinized starch [51]. This causes more soluble substances to be extracted by cooking water, resulting in increased cooking losses. This is why

Sherpa rice (Taiwan) experiences lower cooking losses compared to analogue rice (including optimal analogue rice, analogue rice "Fukumi," and analogue rice without porang). This is because Sherpa rice (Taiwan) is harvested as paddy rice.

According to **Table 5**, the cooking time for optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the other comparison products. The cooking time for optimal analogue rice was 30.69 min, which was shorter than that of Sherpa rice (Taiwan) at 35.12 min. The shorter cooking time for analogue rice is due to the gelatinization process that occurs during

extrusion [13]. Pre-processing methods (such as extrusion) help water absorption and speed up starch gelatinization during cooking [52]. This can reduce the cooking time of analogue rice. Moreover, optimal analogue rice features larger pores than its counterparts (**Figure 1**). The increased porosity of analogue rice facilitates more efficient water absorption, expediting the cooking process [53]. This leads to the minimum cooking time for optimal analogue rice.

### Pasting behavior

**Table 6** shows that all pasting behavior parameters of the optimal analogue rice formulation were significantly ( $p < 0.05$ ) different from those of the control sample. The peak viscosity of the optimal analogue rice was 2,822 cP, which was lower than that of Sherpa rice (Taiwan) at 6,348 cP. Peak viscosity indicates the ability of starch granules to expand and absorb water to their maximum before the granule structure begins to break down owing to heat and agitation [54]. High-fiber Arrowroot flour can inhibit gelatinization, reducing the swelling capacity of starch granules and resulting in lower peak viscosity [55].

**Table 6** Results of pasting behavior analysis.

No.	Parameters	Optimal Analogue Rice	Analogue Rice Without Porang	“Fukumi” Analogue Rice (Indonesia)	Sherpa Rice (Taiwan)
1	Peak viscosity (cP)	2,822 <sup>b</sup>	1,117 <sup>c</sup>	685 <sup>d</sup>	6,348 <sup>a</sup>
2	Through viscosity (cP)	2,511 <sup>b</sup>	826 <sup>c</sup>	554 <sup>d</sup>	3,219 <sup>a</sup>
3	Final viscosity (cP)	3,850 <sup>b</sup>	1,660 <sup>c</sup>	872 <sup>d</sup>	5,260 <sup>a</sup>
4	Breakdown viscosity (cP)	310 <sup>b</sup>	291 <sup>c</sup>	131 <sup>d</sup>	3,129 <sup>a</sup>
5	Setback viscosity (cP)	1,138 <sup>b</sup>	834 <sup>c</sup>	318 <sup>d</sup>	2,041 <sup>a</sup>
6	Gelatinization temperature (°C)	55.41 <sup>c</sup>	66.69 <sup>b</sup>	50.17 <sup>d</sup>	67.25 <sup>a</sup>

\*Different notations on the same line indicate significant differences at  $\alpha = 0.05$  (5%).

As shown in **Table 6**, the viscosity of the optimal analogue rice trough was significantly ( $p < 0.05$ ) different from that of the control. The viscosity of the optimal analogue rice trough was 2511 cP, which was lower than that of Sherpa rice (Taiwan) at 3,219 cP. The trough viscosity indicates the stability of starch viscosity against heat and stirring. Non-starch components (e.g., crude fiber) are believed to lower the trough viscosity. Non-starch components in arrowroot flour hinder water-starch binding. Additionally, fiber and non-starch compounds can break down the gel structure, further reducing the trough viscosity values [56].

Based on **Table 6**, the final viscosity of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the reference product. The final viscosity of the optimal analogue rice was 3,820 cP, which was lower than that of Sherpa rice (Taiwan) (5,308 cP). After heating, the final viscosity was measured after cooling the starch paste. This parameter indicates the ability of a material to form a stable gel that

resists stirring and cooling [57]. The high amylose content in arrowroot flour is believed to hinder starch granule development and gel formation, leading to a lower final viscosity [58].

As shown in **Table 6**, the breakdown viscosity of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the comparison product. The breakdown viscosity of the optimal analogue rice was 310 cP, which is lower than that of Sherpa rice (Taiwan) (3,129 cP). The breakdown viscosity was calculated by subtracting the trough viscosity from the peak viscosity. This value indicates the extent to which viscosity decreases due to starch granule rupture and gel breakdown during heating. The breakdown viscosity is a measure of starch stability against heat and mechanical shear force [59]. The higher the breakdown viscosity, the lower the stability of the starch upon heating.

According to **Table 6**, the setback viscosity of the optimal analogue rice was significantly different ( $p < 0.05$ ) from that of the reference product. The setback

viscosity of the optimal analogue rice was 1,138 cP, which was lower than that of Sherpa rice (Taiwan) (2,041 cP). Setback viscosity measures the increase in the viscosity of the starch paste when cooled after cooking. This indicates the tendency of starch to undergo retrogradation [60]. The level of starch retrogradation can be affected by the amylose-amylopectin ratio and branching structure of amylopectin [61]. The setback viscosity was calculated from the difference between the final and trough viscosities [54].

**Table 6** shows that the gelatinization temperature of the optimal analogue rice was significantly different from that of the comparison product ( $p < 0.05$ ). The optimal analogue rice had a gelatinization temperature of 55.41 °C, which was lower than that of Sherpa rice (Taiwan) at 67.25 °C. This difference is likely due to the extrusion process used in producing the analogue rice, which acts as a pre-gelatinization step and reduces the temperature required for gelatinization [23]. The gelatinization temperature of the optimal analogue rice was higher than that of the “Fukumi” analogue rice; however, its cooking time was shorter. This can be attributed to the extrusion process, which often produces a porous and partially pre-gelatinized structure that allows water to penetrate rapidly during cooking, thereby reducing the time required for full hydration and softening. In contrast, the “Fukumi” analogue rice likely has a denser, more compact structure, which slows water

absorption despite its lower gelatinization temperature. Additionally, the glucomannan content in porang flour may affect this; glucomannan’s capacity to absorb water increases the moisture level of analogue rice [62]. This higher moisture content facilitates the expansion and gelatinization of starch molecules at lower temperatures.

#### Hydrolysis Index (HI) and Estimated Glycemic Index (eGI)

As shown in **Table 7**, the optimal analogue rice hydrolysis index was significantly ( $p < 0.05$ ) different from that of the comparison product. The optimal rice analogue hydrolysis index of 2.22 is lower than that of Sherpa rice (Taiwan) (7.26). The hydrolysis index measures the ratio that indicates how quickly a substance, mainly starch or carbohydrates, is broken down into simpler molecules through enzymatic hydrolysis. The hydrolysis index (HI) was calculated as the Area Under the Curve (AUC) of glucose released from the food sample divided by the AUC of glucose from the reference standard [63]. The high dietary fiber content of arrowroot flour is believed to affect the hydrolysis index. Dietary fiber can block the amylase enzyme from breaking down starch, so hydrolysis is slower and the index is lower [64]. Glucomannan can form a gel that increases viscosity, thereby slowing starch hydrolysis and glucose absorption in the intestine. This effect also reduces the hydrolysis index.

**Table 7** Hydrolysis index and eGI analysis results.

No	Parameters	Optimal Analogue Rice	Analogue Rice Without Porang	“Fukumi” Analogue Rice (Indonesia)	Sherpa Rice (Taiwan)
1	Hidrolisis Index/HI	2.22 ± 0.081 <sup>d</sup>	7.92 ± 0.089 <sup>b</sup>	16.94 ± 0.449 <sup>a</sup>	7.26 ± 0.364 <sup>c</sup>
2	estimated Glycemic Index (eGI)	40.93 ± 0.045 <sup>d</sup>	44.06 ± 0.049 <sup>b</sup>	49.01 ± 0.246 <sup>a</sup>	43.70 ± 0.200 <sup>c</sup>

\*Different notations on the same line indicate significant differences at  $\alpha = 0.05$  (5%).

Based on **Table 7**, the eGI of the optimal analogue rice was significantly ( $p < 0.05$ ) different from that of the comparison product. The estimated glycemic index of optimal analogue rice was 40.93, which was lower than that of Sherpa rice (Taiwan) (43.70). The glycemic index (GI) measures the rate at which carbohydrates increase blood sugar levels after consumption. The high

glucomannan content in porang tubers acts as water-soluble fiber. The high dietary fiber content is believed to lower the GI of analogue rice. Dietary fiber can form a matrix outside the granules, inhibiting carbohydrate digestion [23]. Slower digestion of carbohydrates leads to slower absorption of blood glucose.

This study developed an analogue rice formulation made from rice, arrowroot, and porang flours using the MOCD optimization method. A limitation of this study lies in its emphasis on ingredient composition, while excluding critical processing parameters such as extrusion temperature, screw speed, and moisture content during processing. In addition, the MOCD optimization results may not be fully valid under different conditions, such as variations in raw material characteristics, moisture content, or particle size. This opens opportunities for future research to refine the production of analogue rice based on the formulation developed in this study.

### Conclusions

The optimized formulation of analogue rice, prepared from a mixture of rice flour, arrowroot flour, and porang flour using a pasta extruder, significantly influenced WAI, hardness, whiteness, and swelling power. ANOVA results indicated significant differences in chemical composition, cooking characteristics, WAR, cooking properties, texture profile, pasting behavior, and eGI between the optimized analogue rice and the comparison products. Future studies should include sensory analysis. The restructured rice developed in this study has the potential for large-scale implementation and commercialization as a functional food to help prevent obesity and diabetes mellitus.

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### Credit author statement

**Alfikri Rasyaki Akhmad:** Investigation; Data Curation; Writing - Original Draft; Visualization. **Ahmad Zaki Mubarok:** Writing - Review & Editing; Supervision; Funding acquisition. **Aji Sutrisno:** Resources. **Jenshinn Lin:** Supervision; Resources. **Simon Bambang Widjanarko:** Conceptualization; Methodology; Supervision; Project administration.

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