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Characterization of texture and microstructure of instant analog rice based on soybean–seaweed formulation

Karakterisasi tekstur dan mikrostruktur beras analog instan berbasis formulasi kedelai–rumput laut

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Abstract

The prevalence of type 2 Diabetes Mellitus (T2DM) continues to rise, and the consumption of high-glycemic index white rice contributes to postprandial hyperglycemia. Alternatives with a low glycemic index that are practical and nutritionally rich remain limited. This study aimed to evaluate the texture and microstructure of instant analog rice based on soybean and seaweed to support T2DM risk management. A completely randomized design with three replicates per treatment was used. The formulations included soybean: seaweed ratios of 40%:60% (P2), 50%:50% (P3), and 60%:40% (P4), along with 100% instant rice as the control (P1). Texture was analyzed using Texture Profile Analysis, and microstructure was observed with a Scanning Electron Microscope (magnification 2000×, 15 kV). Results, significant differences were observed in hardness (P3: 5.21 N), cohesiveness (P2: 0.62), and resilience (P2: 0.41). SEM images showed more porous granules in P2–P4, which correlated with lower hardness and faster rehydration. Formulation P4 (60% soybean:40% seaweed) exhibited moderate hardness (4.87 N), acceptable cohesiveness, and a porous microstructure, supporting its nutritional value and functional properties. In Conclusion, instant analog rice P4 has the potential to serve as a functional food that is practical for T2DM prevention and management, providing a suitable texture and nutritional benefits that support metabolic health.

Keywords: Food Texture, *Eucheuma cottonii, Glycine max* L. Merr., Rice analog, Scanning Electron, Type 2 Diabetes Mellitus

Abstrak

Prevalensi Diabetes Mellitus Tipe 2 terus meningkat, dan konsumsi beras putih dengan indeks glikemik tinggi berkontribusi terhadap hiperglikemia postprandial. Alternatif pangan pokok dengan IG rendah yang praktis dan bernilai gizi tinggi masih terbatas. Penelitian ini bertujuan mengevaluasi tekstur dan mikrostruktur beras analog instan berbasis kedelai dan rumput laut untuk mendukung pengelolaan risiko T2DM. Penelitian menggunakan Rancangan Acak Lengkap dengan tiga ulangan per perlakuan. Formulasi meliputi kedelai : rumput laut 40%:60% (P2), 50%:50% (P3), dan 60%:40% (P4), serta kontrol beras instan 100% (P1). Analisis tekstur dilakukan dengan Texture Profile Analysis, sedangkan mikrostruktur diamati menggunakan Scanning Electron Microscope (perbesaran 2000×, 15 kV). Hasil menunjukkan perbedaan signifikan pada hardness (P3: 5,21 N), cohesiveness (P2: 0,62), dan resilience (P2: 0,41). SEM memperlihatkan granula lebih berpori pada P2–P4, berkorelasi dengan hardness lebih rendah dan rehidrasi lebih cepat. Formulasi P4 (60% kedelai: 40% rumput laut) memiliki hardness moderat (4,87 N), cohesiveness dapat diterima, dan mikrostruktur berpori yang mendukung nilai gizi dan sifat fungsional. Kesimpulan, beras analog instan P4 berpotensi sebagai pangan fungsional yang praktis untuk pencegahan dan pengelolaan T2DM, dengan tekstur yang sesuai dan kandungan nutrisi yang mendukung kesehatan metabolik.

Kata Kunci: Beras analog, diabetes melitus tipe 2, *Glycine max* L. Merr., *Eucheuma cottonii*, tekstur, *scanning electron microscope*

Introduction

Rice consumption remains central to dietary patterns in Asia, particularly in Indonesia, where more than 95% of the population relies on rice as their primary staple. This dependence coincides with the growing burden of type 2 Diabetes Mellitus (T2DM), with a prevalence projected to reach 21.3 million cases in Indonesia by 2030 (IDF, 2019). The high glycemic index (GI) of white rice, influenced by its amylose–amylopectin composition, accelerates starch digestion, triggers rapid insulin responses, and contributes to postprandial hyperglycemia (Li et al., 2024). These mechanisms explain why excessive rice intake is strongly associated with an elevated diabetes risk, underscoring the urgent need for staple alternatives that can moderate the glycemic impact.

Analog rice formulated from *Glycine max* L. Merr (soybean) and *Eucheuma cottonii* (seaweed) has emerged as a promising alternative. Soybeans provide protein, dietary fiber, antioxidants, and isoflavones, while seaweed provides hydrocolloids such as agar, carrageenan, and alginate, which act as natural binders to mimic the granular structure of conventional rice. The inclusion of *Pandanus amaryllifolius* leaves further enhanced the sensory quality and introduced flavonoid-based antioxidants. Together, these components create a nutritionally enriched, low-glycemic alternative that is particularly relevant for individuals with T2DM.

Despite these advances, a significant research gap remains. To date, no study has systematically examined the texture and microstructure of instant analog rice produced using soybean–seaweed formulations. Texture is a critical determinant of consumer acceptance and directly influences rehydration behavior and starch bioaccessibility, both of which are associated with glycemic control (Ramadhan et al., 2024; Saragih et al., 2019).

During the production of instant analog rice, *Eucheuma cottonii* functions as a natural adhesive, enabling the final product to maintain the shape and physical characteristics of conventional rice (Setiawan et al., 2022). In addition, *Pandanus amaryllifolius* leaves contain terpenoids that impart a distinctive aroma and flavonoids that provide antioxidant activity (Kurniasari et al., 2020).

Modern lifestyles and the demand for low-calorie, convenient foods among individuals with T2DM highlight the need for instant analog rice that is easy to prepare while maintaining a desirable quality and texture (Setiawan et al., 2022). Texture analysis is crucial for evaluating consumer acceptance, palatability, and functional properties, such as rehydration and starch digestibility. Recent studies have confirmed that texture profiling provides valuable insights into food quality and its influence on the glycemic response (Ramadhan et al., 2024).

The novelty of this research lies in its integrated approach, which evaluates texture through Texture Profile Analysis (TPA) and links these parameters to microstructural features observed via Scanning Electron Microscopy (SEM). By analyzing the differences across formulations and correlating the SEM pore architecture with TPA metrics such as hardness, cohesiveness, and resilience, this study aims to identify the optimal instant analog rice formulation. These findings provide new insights into how processing and ingredient interactions shape functional properties, advancing the design of low-GI staple foods for T2DM prevention and management.

This study aimed to evaluate the texture and microstructure of instant analog rice formulated from *Glycine max* L. Merr, *Eucheuma cottonii*, and *Pandanus amaryllifolius* leaves, with the goal of determining the optimal formulation that balances consumer acceptability, nutritional quality, and glycemic control.

Methods

Experimental Design

The study employed a Completely Randomized Design (CRD) with three experimental formulations and one control. The CRD was chosen because all experimental units were considered homogeneous, allowing treatments to be randomly assigned and minimizing bias in the measurement of the texture and microstructural parameters. This design facilitates a straightforward statistical analysis, ensuring that the observed differences can be attributed primarily to the formulation rather than external factors.

The formulation selection was based on initial studies identifying optimal organoleptic outcomes (Setiawan et al., 2022). Three formulations of *Glycine max* L. Merr and *Eucheuma cottonii* flour were tested: P2 (40%:60%), P3 (50%:50%), and P4 (60%:40%), with a commercial 100% instant rice serving as the control (P1). Each formulation was replicated thrice, resulting in a total of 12 samples (Hanafiah, 2016).

All samples were prepared under standardized conditions, including identical cooking, drying, rehydration, storage, and measurement. Texture was analyzed using Texture Profile Analysis (TPA), and the microstructure was examined using SEM.

Tools and Materials

The tools used for analog rice production included basins, measuring cups, spoons, plates, and solets, whereas instant rice production required dehydrators, vacuum devices, vacuum-sealable plastic bags, and sealers. Texture analysis and microstructure observations were conducted using a TA1 Texture Analyzer (Ametek Inc., USA) and a Scanning Electron Microscope (SEM; QUANTA FEG 650, Field Electron and Ion Company, USA).

The study materials consisted of organic *Glycine max* L. Merr flour obtained from Kusuka Ubiku, Bantul Regency, Yogyakarta, and *Eucheuma cottonii* flour sourced from Pasuruan, East Java. These flours were combined with additional ingredients, including tapioca flour (5%), cornstarch (5%), carboxymethyl cellulose (CMC; 0.5%), and *Pandanus amaryllifolius* leaves.

Research Stages

Analog Rice Production

Analog rice was prepared as described by Setiawan et al. (2022). All the ingredients were mixed until homogeneous and then molded using an extrusion tool to resemble rice grains. The analog rice was then processed into instant analog rice.

Instant Analog Rice Production

The mixed analog rice ingredients were steamed after rinsing once with water (Kurniasari et al., 2020). Cooked analog rice was frozen at −20°C for 24 h (Panasonic, Japan), thawed at room temperature for 30 min, and subsequently dried in a dehydrator at 50°C for 8 h (GEA GETRA, Indonesia). After drying, the instant analog rice was packaged.

Analysis Method

Texture Profile Analysis (TA1 User Manual, 2013)

Texture Profile Analysis (TPA) of instant analog rice was conducted using a Lloyd Instrument texture analyzer (Lloyd Material Testing TA1 Series, Ametek Inc., US). For each test, a subsample of 10 grains was selected as representative units, following previous studies that demonstrated that small-grain sampling is sufficient for the texture evaluation of rice and analog rice products when grains are homogeneous in size and shape (Ramadhan et al., 2024). The number of grains was chosen to balance the measurement precision with the instrument sensitivity, as larger sample sizes may introduce variability owing to uneven grain orientation.

Grains were randomly selected from the homogenized batches to avoid bias and ensure representativeness. Homogenization was achieved by thoroughly mixing each formulation prior to sampling, and random selection was performed using a simple random-draw method. The sample was pressed with a 35 mm diameter probe at a speed of 0.5 mm/s, and the results were recorded using NEXYGENPlus™ software.

The parameters measured included hardness, cohesiveness, adhesiveness, resilience, and springiness. Each measurement was performed in duplicate (duplo) for each sample to ensure the reliability and reproducibility of the results.

Scanning Electron Microscope (QUANTA FEG 650, Field Electron and Ion Company, USA, user manual, 2023).

An aluminum (Al) specimen stub was cleaned with acetone and dried using a lint-free tissue to prevent any contamination. A carbon double-sided adhesive tape was affixed to the stub surface to facilitate sample mounting, and the sample was carefully placed on the adhesive tape. Gold (Au) coating was applied using a Quorum Q150R S Plus sputter coater (Quorum Technologies Ltd., UK) for 35 s at a current of 20 mA, producing an approximate gold layer thickness of 30 nm.

Following coating, the specimen was loaded into the chamber of a Field Emission Scanning Electron Microscope (FESEM; QUANTA FEG 650, Field Electron and Ion Company, USA). Imaging was conducted under low vacuum conditions (60 Pa) with a large-field detector (LFD). The accelerating voltage was set to 15 kV, which provided sufficient resolution for observing the surface morphology while minimizing the charging effects. Microstructural observations were performed at magnifications ranging from 500× to 5000×, focusing on representative areas of the grain surface to capture the porosity, roughness, and granule cohesion. Each sample was observed at three different points to ensure reproducibility and account for structural variability.

Data Analysis

TPA data were analyzed using SPSS version 25. Normality and homogeneity were checked to determine the appropriate statistical tests. For normally distributed and homogeneous data, One-Way ANOVA followed by Bonferroni post hoc tests was used. When the data were normally distributed but not homogeneous, Welch's ANOVA with Games–Howell post hoc test was applied. Non-normal data were analyzed using the Kruskal–Wallis test, followed by Mann–Whitney U pairwise comparisons ($p < 0.05$).

The optimal formulation was determined using the Multiple Attribute Method (MAM). Each parameter (hardness, cohesiveness, adhesiveness, resilience, and springiness) was assigned a weight based on its relevance to the product quality and consumer acceptance. Weighted scores were calculated for each formulation, and the formulation with the highest composite score was selected as the optimal formulation.

Result and Discussion

Characteristics of Instant Analog Rice

Analog rice and instant analog rice production involves several stages, beginning with ingredient preparation, mixing, and extrusion to form analog rice (Setiawan et al., 2022). The production of instant analog rice then continues with steaming, freezing, and drying using a dehydrator (Kurniasari et al., 2020).

The instant analog rice produced in all formulations was smaller than regular rice and exhibited a cylindrical shape resembling cooked brown rice (Figure 1). The product was greenish-brown, reflecting the composition of the ingredients. The brown hue results from non-enzymatic browning reactions during processing, primarily Maillard reactions and caramelization, as well as the carotenoid content of *Eucheuma cottonii* (Falah et al., 2022; Kasran et al., 2021; Al-Abbasy et al., 2024). The processing temperature and duration are key factors influencing these browning reactions, thereby affecting both the color and overall quality of the product.

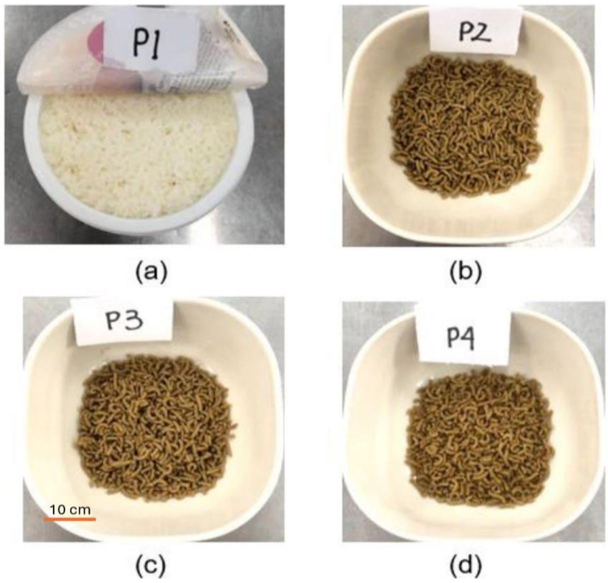

Figure 1. Comparison of instant analog rice formulations and commercial rice. (a) Commercial rice (P1), (b) Analog rice formulation P2 (40% *Glycine max*: 60% *Eucheuma cottonii*), (c) Analog rice formulation P3 (50%:50%), (d) Analog rice formulation P4 (60%:40%). The scale bar represents 10 cm in length.

The greenish tone observed in the instant analog rice was attributed to the chlorophyll content in the seaweed flour, which ranged from 1.31 to 2.20 mg/g (Kasran et al., 2021; Minsas et al., 2023). This chlorophyll contributes to the distinctive color and may also enhance the functional properties of rice due to its bioactive potential.

Texture Profile Analysis (TPA)

The texture parameters observed in the instant analog rice formulated with various ratios of *Glycine max* L. Merr and *Eucheuma cottonii* flour included hardness, cohesiveness, springiness, adhesiveness, and resilience (Table 1).

Table 1 shows that the hardness values differed significantly ($p < 0.05$) among the formulations. The highest hardness was observed in P2 (375.79 ± 45.47), whereas the control (P1) exhibited the lowest value (21.92 ± 2.97). The variations in hardness were closely related to the ratio of soybean to seaweed flour. In P4 (290.82 ± 43.03), the higher soybean content (60%) contributed to a reduction in hardness, likely because of the fat content in soybean flour weakening starch–protein interactions. This observation aligns with the SEM results, where P4 exhibited a more porous and less compact structure than P2 and P3. Conversely, P2 exhibited denser granule packing and stronger particle adhesion, reflecting the higher proportion of seaweed hydrocolloids functioning as natural gelling agents. The combined TPA and SEM findings indicated that formulations with balanced soybean–seaweed ratios (P2 and P3) produced analog rice with superior hardness and structural integrity relative to the control and P4.

Previous studies have supported these findings. Incorporating soy flour into rice formulations has been shown to decrease hardness due to the fat content (Anindita et al., 2020; Amelia, 2019). Setiawan et al. (2022) also reported that increasing the amount of *Glycine max* L. Merr flour reduced the fat content in analog rice, contributing to lower hardness in P4. Additionally, the gelling properties of *Eucheuma cottonii* act as a natural adhesive, enhancing structural cohesion and reducing its brittleness (Damat et al., 2020). However, the reduced *Eucheuma cottonii* content in P4 corresponded to lower hardness values, confirming the importance of seaweed flour in maintaining structural integrity.

Cohesiveness reflects the strength of internal bonding within a product, indicating the extent to which a material can deform before it breaks (Rosenthal & Thompson, 2021; Szczesniak, 2002). Significant differences ($p < 0.05$) were observed among the formulations, with P2 and P3 exhibiting the highest cohesiveness values (0.58 ± 0.12 and 0.58 ± 0.09, respectively), compared to the control (P1, 0.32 ± 0.05). This nearly two-fold increase demonstrates that *Eucheuma cottonii* flour substantially strengthened the internal bonding of analog rice. The water-binding ability of seaweed flour likely contributed to the compact and sturdy structure observed in P2 and P3, which resisted breakage more effectively than the control.

From a health perspective, higher cohesiveness may have implications for individuals with type 2 diabetes mellitus (T2DM). A more compact rice structure could potentially slow starch gelatinization and digestion, thereby moderating postprandial glucose release. However, it should be noted that the present study did not directly measure the glycemic index (GI); therefore, these metabolic implications remain speculative.

The limitations of this study include the relatively small sample size (10 grains per group), absence of chemical composition and moisture content analysis, lack of sensory evaluation, and the absence of GI measurement. These factors limit the generalizability of findings and prevent direct linkage between physical texture and potential health benefits

Taken together, these results indicate that *Eucheuma cottonii* flour enhances the cohesiveness of analog rice. However, further studies incorporating chemical composition, sensory evaluation, and metabolic analyses are required to confirm its functional and health-related benefits.

Springiness refers to the rate at which a compressed material recovers its original shape after deformation (Kusumayanti et al., 2022). As shown in Table 1, no significant differences in springiness were observed among the formulations ($p > 0.05$). The highest springiness was recorded for P2 (0.71 ± 0.03), whereas the control (P1) had the lowest value (0.05 ± 0.09). Although formulations P2, P3, and P4 exhibited higher springiness than the control, the overall elasticity of instant analog rice remained relatively low. These findings are consistent with previous studies on analog rice prepared from purple sweet potato, cassava, and corn flour, which reported springiness values ranging from 0.5–0.9 (Kusumayanti et al., 2022). Similarly, corn flour analog rice supplemented with carrageenan and konjac showed springiness values between 0.56 and 0.86 (Kurniasari et al., 2020). The higher springiness of P2 can be attributed to the 60% inclusion of *Eucheuma cottonii* flour. Additionally, the proportion of *Glycine max* L. Merr flour influenced springiness, as the fat content in soybean flour (edamame) may reduce elasticity, similar to its effect on hardness (Kurniasari et al., 2020; Setiawan et al., 2022).

Adhesiveness is the force required to detach a food sample from a surface (Kusumayanti et al., 2022; Pramono et al., 2021). No significant differences were observed in the adhesiveness among the formulations ($p > 0.05$; Table 1). P2 exhibited the highest adhesiveness (5.92 ± 3.42), while P4 had the lowest value (2.78 ± 1.21). The reduction in adhesiveness in P3 and P4 may be due to the lower proportion of *Eucheuma cottonii* flour compared to P2. The higher adhesiveness in P2 is likely linked to the 60% seaweed flour content, which promotes water binding and gel formation. This effect is consistent with the findings of gluten-free pasta enriched with red seaweed, where adhesiveness increased with higher seaweed concentrations (Sholichah et al., 2021). Furthermore, Setiawan et al. (2022) reported a total fiber content of 8.04 g/100 g in their P2 formulation. Elevated fiber enhances water absorption within the gelatinized matrix during instant analog rice production, contributing to increased stickiness (Fradinho et al., 2019).

Table 1. Texture Profile Analysis (TPA) of instan analog rice

Parameters	Formulations (mean ± standard deviation)			
	P1	P2	P3	P4
Hardness (N)	21,92±2,97^{b}	300,51±21,99^{a}	375,79±45,47^{a}	290,82±43,03^{a}
Cohesiveness	0,32±0,05^{a}	0,58±0,12^{b}	0,58±0,09^{b}	0,55±0,05^{ab}
Springiness	0,05±0,09	0,71±0,03	0,69±0,01	0,67±0,02
Adhesiveness	4,39±1,20	5,92±3,42	4,51±1,94	2,78±1,21
Resilience	0,02±0,03^{c}	0,66±0,05^{a}	0,45±0,06^{b}	0,58±0,08^{ab}

Additional information:
Data are presented as the mean of three replicates. Different superscript letters within a column denote statistically significant differences ($\alpha<0.05$). P2, P3, and P4 are instant analog rice formulations using *Glycine max L. Merr* and *Eucheuma cottonii* with respective ratios (40%:60%); (50%:50%); and (60%:40%).

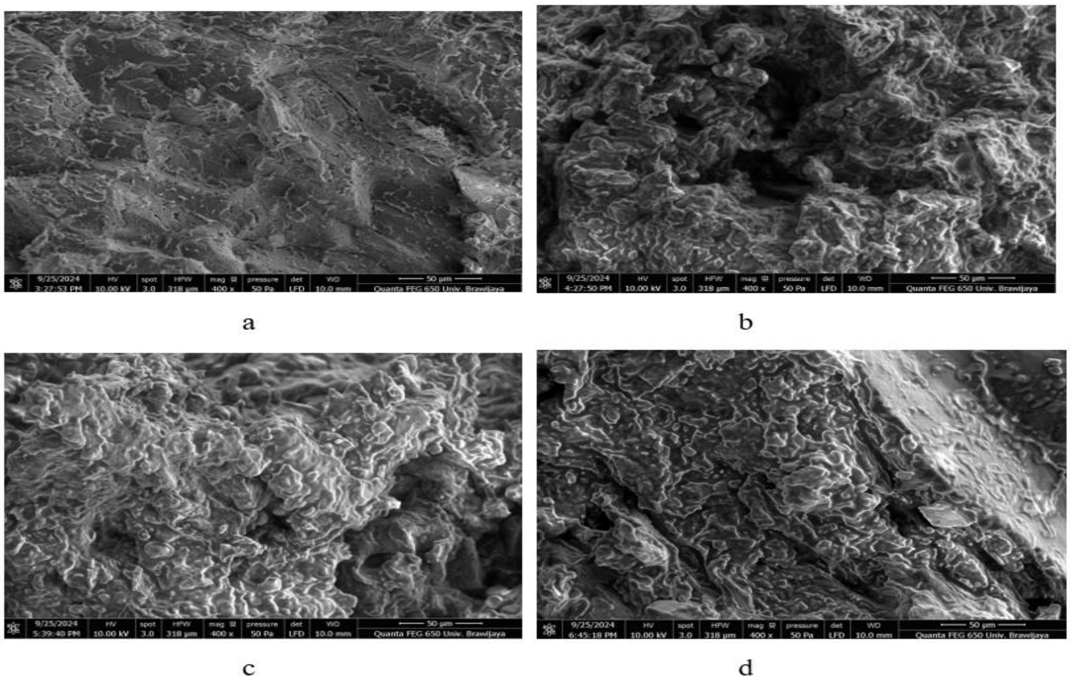

Figure 2. Instant analog rice with formulation P1 (control) commercial products (a), *Glycine max* L. Merr and *Eucheuma cottonii* flour formulations: P2 (40%:60%) (b); P3 (50%:50%) (c); and P4 (60%:40%) (d). Images were obtained using a scanning electron microscope, 400X magnification, the rice section was taken from a cross-section.

Resilience refers to a product's ability to recover its original shape during decompression, which is typically measured during the initial compression or first bite (Yang et al., 2024). As shown in Table 1, the resilience values differed significantly among the formulations ($p < 0.05$). Formulations P2, P3, and P4 exhibited significantly higher resilience than the control

(P1). The highest resilience was observed in P2 (0.66 ± 0.05), whereas the lowest was observed in P1 (0.02 ± 0.03). Despite these differences, the resilience of P2–P4 remained lower than the typical commercial rice values (0.20–0.30) reported in previous studies (Chen et al., 2017).

Analog rice formulated with MOCAF and rice flour has been shown to achieve resilience values comparable to commercial rice, likely due to the amylose content in MOCAF and rice flour, which enhances the structural similarity to conventional rice (Liu et al., 2022; Pramono et al., 2021).

Scanning Electron Microscope

SEM analysis revealed distinct morphological differences between the analog rice formulations (P2–P4) and commercial instant rice (P1) (Figure 2). The control (P1) exhibited a dense and smooth surface with minimal voids, indicating a compact and uniform matrix. In contrast, the analog rice samples (P2–P4) displayed rougher, more porous surfaces with visible hollowness, reflecting a looser internal structure. These variations result from the ingredient composition and processing methods, including high-fiber incorporation and hot extrusion. Extrusion at elevated temperatures (70–90°C) promotes complete starch gelatinization, disrupts intramolecular bonds, and encourages granule fusion, thereby producing a porous matrix (Sari et al., 2021).

Formulations with higher soybean or fermented sorghum content have been shown to reduce the Water Absorption Index (WAI) and increase structural compactness, influencing surface morphology (Putri et al., 2020; Wahyuni et al., 2022). The microstructural differences corresponded directly with the texture measurements: analog rice (P2–P4) exhibited markedly higher hardness values (290–300 N) compared to 21 N P1. This 14-fold increase underscores the role of a denser and more porous matrix in resisting compressive forces. Hardness is a critical texture parameter that reflects the force required to achieve a given deformation (Szczesniak, 2002). Elevated hardness in analog rice is attributed to the fibrous content and protein–starch interactions. Prior studies have demonstrated that pore size, granule cohesion, and surface texture are closely associated with instrumental texture metrics such as hardness and adhesiveness (Chen et al., 2022; Rahman et al., 2021), reinforcing the need to integrate microstructural and physical analyses for product evaluation.

Best Formulation

The optimal formulation was determined using the Zeleny method based on hardness, cohesiveness, springiness, adhesiveness, and resilience, yielding scores of P2 = 0.31, P3 = 0.21, and P4 = 0.10, respectively. Based on these results, P4 was identified as the optimal formulation for producing instant analog rice.

However, this study has several limitations that should be acknowledged. First, the evaluation focused solely on texture and microstructural parameters without direct measurement of the glycemic index or in vivo glycemic response, limiting conclusions regarding potential functional benefits for individuals with T2DM. Second, only specific ratios of soybean and seaweed flour were tested, and alternative formulations or additional functional ingredients were not explored. Third, sensory evaluation was not conducted; therefore, consumer acceptability and perception of the analog rice could not be fully inferred. Finally, the study was performed under controlled laboratory conditions, which may not fully represent industrial-scale production or typical household preparations. These limitations underscore the need for further research integrating texture and microstructural analyses with nutritional, sensory, and clinical evaluations to comprehensively validate the effectiveness of instant analog rice formulations.

Conclusion

This study demonstrates that the microstructural characteristics of analog rice are closely associated with its instrumental texture. Denser and more cohesive structures, reinforced by soybean protein and seaweed hydrocolloids, corresponded to higher hardness and cohesiveness, confirming that the microstructure directly influences texture performance. These results indicate that analog rice formulations, particularly those enriched with soybean and seaweed flour, are viable alternative staple foods, offering improved structural integrity compared to conventional instant rice. From a health perspective, the compact texture of analog rice may contribute to slower starch digestion and potentially lower postprandial glycemic responses, highlighting its relevance in dietary management in individuals with type 2 diabetes mellitus (T2DM).

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