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Analogue Rice from *Amorphophallus muelleri* and Potato with Enhanced Nutritional Properties: Lower Glycemic Index and Higher Fibre Content

Kisroh Dwiyono[1], Nor Elliza Tajidin[2]*, Maman Abdurachman Djauhari[3], Elisa Azura Azman[2], Nur Syahirah Abdul Rashid[4], Viktor Vekky Ronald Repi[5], and Noverita[1]

[1]*Department of Biology-Agriculture, Universitas Nasional Jakarta, 12520 Jakarta, Indonesia*
[2]*Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[3]*KH Badruzzaman University College of Islamic Religion, 44161 Garut, Indonesia*
[4]*Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, Sungai Batang Road, Mile 10, 90000 Sandakan, Sabah, Malaysia*
[5]*Department of Engineering Physics, Universitas Nasional Jakarta, 12520 Jakarta, Indonesia*

ABSTRACT

In the year 2024, the world population is expected to reach 8.2 billion. At an estimated annual growth rate of 0.8%, the United Nations predicts that it will reach 9.7 billion by 2050 and 10.4 billion in the 2080s. Further, according to the World Food Programme, as many as 309 million people are facing chronic hunger. Sadly, the number of acutely hungry people and malnutrition continues to increase. Inline with the second and third goals of the 2030 Agenda for Sustainable Development, to end hunger, achieve food security, ensure healthy lives and promote well-being, this paper deals with an initiative to find the production of analogue rice, with a new composition of ingredients. The materials used are Indonesian konjac, potatoes, and several auxiliary ingredients such as glyceryl monostearate (GSM), sago, and water. The methods used were weighing, mixing, heating, and moulding using an extruder. Its objectives are to determine the optimum composition of the ingredients used and to assess its nutritional characteristics. More importantly, the analogue rice produced using this formula possessed the nutritional characteristics of healthy food. Additionally, the easy availability of the ingredients has the potential to contribute

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E-mail addresses:
kisroh.dwiyono@civitas.unas.ac.id (Kisroh Dwiyono)
elliza.tajidin@upm.edu.my (Nor Elliza Tajidin)
maman_djauhari@institutpendidikan.ac.id (Maman Abdurachman Djauhari)
elisa@upm.edu.my (Elisa Azura Azman)
nursyahirahrashid96@gmail.com (Nur Syahirah Abdul Rashid)
vekky_repi@civitas.unas.ac.id (Viktor Vekky Ronald Repi)
noverita@civitas.unas.ac.id (Noverita)
* Corresponding author

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to alleviating the food affordability and availability crises. The conclusion on the best compositions was Indonesia konjac (39.50 %), *S. tuberosum* (19.50 %), Sago (9.50 %, Glyceryl Monostearate (GSM) (2.00 %), and water (29.50 %) (formula IV).

Keywords: Analogue rice, food security, Indonesian konjac, nutrition, *Solanum tuberosum*

INTRODUCTION

Human survival is one of the principal concerns of the 2030 Agenda for Sustainable Development Goals (SDGs). The first goal of this agenda is to end hunger, achieve food security, improve nutrition and promote sustainable agriculture. The next is to ensure healthy lives and promote well-being for all ages. However, according to the World Food Programme (WFP), unfortunately, the number of acutely hungry people, and thus malnutrition, continues to increase (FSIN, 2024). Almost 4% of the world's population, in 71 countries, is facing chronic hunger. Among them, 12% face emergency levels of hunger and around 0.5% are in the grips of catastrophic hunger (FSIN, 2024). More specifically, according to the United Nations Children's Fund (UNICEF), World Health Organisation (WHO), and World Bank (2023), an estimated 149 million children under the age of 5 were suffering from stunting. Further, currently, nearly half of the deaths among children under 5 years of age are linked to undernutrition, and another 190 million are living with thinness.

It is in the spirit of contributing towards ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture that this research was conducted, and its results were publicised so that authorities around the globe could take necessary actions. This topic is not new, as can be seen in the study by (Tie et al., 2008), where scientists and researchers tried to produce analogue rice (AR in brief) using plant tubers and some special additional ingredients while keeping the nutritional content as similar as possible to that of paddy rice. AR is a form of artificial rice made from various kinds of flour as a substitute for natural rice. Thus, its production process needs to be streamlined to result in characteristics similar to paddy rice, with carbohydrate content similar to or in excess of that in natural rice and sufficient nutritional content, such as protein, starch, and sugars (Sumardiono et al., 2021).

In this study, the Indonesian konjac (IK) tuber was chosen as the principal ingredient, the reason being that the konjac tuber has multiple benefits and has been used as raw material in various industries such as the food and beverage industry, pharmaceutical industry, and cosmetics industry (Widjanarko et al., 2022). The unique characteristics of konjac have also been frequently discussed in many literatures, such as Dwiyono and Djauhari (2019), Pan et al. (2015), and Thanh et al. (2013). More specifically, Dwiyono and Djauhari (2019) mentioned that IK flour contains 6.16% protein, 10.14% crude fibre, and 35.92% glucomannan, which shows its potential for developing healthy artificial food. In relation to this, Harijati et al. (2018) mentioned that IK can be used to control obesity and diabetes. It is also a wild plant which can be easily cultivated across Indonesia and Southeast Asia (Wahidah et al., 2021).

Besides IK, additional carbohydrate sources are needed. According to Santoso et al. (2018) and Hasbullah et al. 2023, potential options include cassava, corn, maize, mocap, sago, sorghum, and soybeans. However, this study utilised potato as it offers a high carbohydrate content (Obong & Parmentier, 2009) and is readily available in Indonesia. IK and potato are good ingredients, but are insufficient to produce high-quality AR, as AR grains need to be solid, resistant to cracking, and non-stick to one another. Sago and glycerol monostearate (GMS) were the additional ingredients to resolve these issues. Finally, water was added as the fifth ingredient to keep the production machine safe from overheating. Thus, IK flour, potato flour, sago starch, GMS, and water were the five ingredients used to produce AR in this study. Although the use of these ingredients is not novel (Tie et al., 2008), determining the optimal composition or percentage of each ingredient to achieve the best results has remained challenging.

Therefore, the present study was carried out: 1. to investigate the different composition of ingredient formulations on the properties of AR and 2. to develop an AR porridge product with a palatable texture and pleasant flavour by adding konjac glucomannan.

MATERIALS AND METHODS

Materials Used

The main raw materials used in this study are porang tubers obtained from porang farmers in Klangon Village, Saradan Subdistrict, Madiun Regency, East Java Province, and potatoes of the "Granola" variety obtained from potato farmers in Dieng Village, Wonosobo Regency, Central Java Province. Sago flour was purchased from the Bogor market, West Java, Indonesia. Porang, potato tubers as the primary ingredient, and sago, GMS, and water as additional components; all of which were sourced from local vendors in Bogor market west Java, Indonesia. Chemicals such as sulphuric acid 98% Merck Germany, potassium permanganate 99% Riedel-de Haen, sodium malonate dibasic 98% Merck Germany, hydrochloric acid 98% Merck Germany, sodium chloride 98.5% Himedia, oxalic acid 98% Merck Germany, sodium sulfate 99% Merck German, aquadest, sodium hydroxide 99% Nepa-Smart, hexane 99% Merck Germany, and ethanol 98% Merck Germany.

The laboratory utilised was equipped with standard tools and instruments, as suggested in the literature, the grinder hammer mill, grinder disc mill, mixer, a double screw extruder, Fourier Transform Infrared (FT-IR) analyser, and a digital optical microscope (DOM) from Bogor Agriculture University.

Methods of Data Collection and Analysis

To determine the best composition formula, it was first written as X% of IK flour, Y% of potato flour, Z% of sago starch, V% of GMS, and W% of water. The principal problem addressed in this research is: "How to find the optimal values of X, Y, Z, V and W?" To answer this question, four composition formulas were considered, and laboratory experiments were conducted for each formula.

The optimal formula was the one which resulted in a product with quality characteristics most similar to those of natural rice. Here, the word "similar" relates to the levels of moisture, ash, fat, protein, carbohydrates, fibre, calcium oxalate, bond profile (functional group), and micro-structural profile. For this purpose, this study encompassed seven analyses:

1. Formulation analysis to make sure that the product possessed the flavour of natural rice.
2. Proximate analysis to compare its chemical composition with that of natural rice.
3. Physical characteristics analysis to examine its significant quality characteristics.
4. Rapid viscosity analysis (RVA) to investigate the peak viscosity of the product. This is linked to the highest level of swelling power exhibited by its starch granules.
5. Whiteness degree analysis to compare the whiteness level of the product and that of natural rice using the Colourimeter Instrument Euclidean (CIE).
6. Fourier transform-infrared (FT-IR) analysis to identify the functional groups present in the material matrix.
7. Micro-structural profile analysis using a digital optical microscope (DOM).

Among these analyses, the data obtained from the first five were subjected to ANOVA followed by multiple comparison analysis, based on Duncan's multiple range test (DMRT).

Starch Content Analysis

A sample of approximately one gram is hydrolysed with 100 ml of 3% HCl in an autoclave for 15 minutes at a temperature of 115 °C. It is then neutralised by adding NaOH 4N and diluted with distilled water to a final volume of 250 ml at pH 7, followed by filtration. A 10 ml aliquot of the filtrate is pipetted and transferred into an Erlenmeyer flask containing 25 ml of Luff Schroll solution. The mixture is heated in an autoclave or with a reflux condenser for 10 minutes until boiling. The mixture is cooled with running water, and 20 ml of 20% KI and 25 ml of 25% H_2SO_4 are added slowly. The mixture is titrated with $Na_2S_2O_3$ 0,1 N until a pale-yellow solution is formed, then 1% starch indicator is added (resulting in a blue solution). The titration continues until the blue colour disappears (denoted as a ml). A blank solution is also titrated (denoted as b ml). The starch content is calculated using Equation 1.

$$\text{Starch Content} = \frac{a \; x \; P \; x \; 0{,}95}{mg \; sample} \text{ x } 100\% \qquad [1]$$

where: P = 25 (constant numerical value)
a = volume of solution titrated

The formulation analysis aimed to evaluate the physical attributes of analogue rice (AR), focusing on its flavour, resemblance to natural rice, and lack of irritants or excessive saltiness.

Method of Production

In this study, the AR production process was carried out using an extrusion machine for the mixing, cooking, kneading, crushing, and forming or moulding processes, as recommended by (Ridwansyah et al., 2020) and (Mishra et al., 2012). AR's production process began with preparing IK flour, potato flour, and sago starch. The percentage combination is mentioned in Table 1.

These ingredients, along with GMS and water, were mixed thoroughly using a mixer for 20 minutes to ensure homogeneity. The resulting mixture was then processed in a double-screw extruder, operated at 96 °C and a speed of 168 revolutions per minute, for 30 minutes. During extrusion, a constant temperature and auger pressure were maintained. After extrusion, the AR was dehydrated in an oven at 45 °C for 30 minutes and then packaged in plastic wrapping for storage.

Determination of Physical Properties

The viscosity of the analogue rice is determined using a Brookfield viscometer model RTV. The viscosity value, expressed in centipoise, is obtained by multiplying the factor on the instrument by the measured value. 2 grams of rice are added to 10 ml of water and stirred, then 90 ml of boiling water is added and cooled until it reaches room temperature. The spindle used is spindle number 4 with a speed of 6 revolutions per minute, and the conversion factor is 1000. This is the procedure for measuring viscosity using a Brookfield RVT viscometer. (i) Attach the spindle as needed, (ii) Pour the sample to be measured into

Table 1
Four experimental formulations for analogue rice production

Formula	IK (%)	Potato (%)	Sago (%)	GSM (%)	Water (%)
I	37.00	27.00	17.00	2.00	17.00
II	27.00	22.00	12.00	2.00	37.00
III	37.00	22.00	12.00	2.00	27.00
IV	39.50	19.50	9.50	2.00	29.50

a beaker and place it under the spindle. Then lower the spindle into the sample by turning the screw at the back, (iii) Adjust the speed setting as required, (iv) Turn on the power and observe the needle; the red needle should be exactly at the 0-100 mark for the specified time (dial reading), (v) Multiply the factor by the dial reading. Factor = speed x spindle number. Example: speed = 30, spindle number = 2, so the factor is 60. To read the dial, press the small lever at the back downward. The speed setting is on the upper dial, and the spindle number is inside the box.

The whiteness degree analysis used a precise colourimetre called Chromametre CR-400 Konica Minolta (Tokyo, Japan), with the BCSF and UCSF samples in the hole through which the light passes, so that no light escapes, and then recording the values of L*, a*, and b*. Whiteness is calculated using Equation 2 (Amalia et al., 2020).

$$W = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{½.} \quad [2]$$

where, W = whiteness, L = Brightness level, between 0 (black) and 100 (white), determined based on visual observation; Δa^* = Total reddish/greenish colour; Δb^* = Total yellowish/bluish colour.

The micro-structure profile from the dried analogue rice sample was placed on a metal stub with double-sided adhesive tape and then coated with gold powder under vacuum to make the sample conductive. The morphology property of analogue rice was observed by using a scanning electron microscope (SEM Philips XL30), and the image was taken at an acceleration potential of 20 kV (Ashri et al., 2014).

RESULTS AND DISCUSSION

As summarised in Table 2, the amylum and amylopectin content varied across the formulas, with Formula IV showing the lowest levels. However, no significant difference was observed in the amylose content across the four experimental analogue rice formulas. The content level is mainly influenced by the amounts of IK, potato, and sago used, as their starch properties determine the final composition. Potato starch has a lower amylose content than other starches, so the percentage of potato in each formula impacts the ratio of amylose to amylopectin (Lal et al., 2024). For example, Formula I, with 27% potato, likely has a higher amylopectin content than Formula IV, which contains only 19.5% potato. Sago starch, rich in amylopectin, also increases amylopectin levels in the formula (Sumardiono et al., 2021). A higher sago content, such as 17% in Formula I, results in more amylopectin, while a lower sago content, like 9.5% in Formula IV, reduces amylopectin levels. Lower amylopectin levels improve AR quality, making Formula IV, which demonstrated the lowest amylopectin content, the optimal choice for producing high-quality and healthy AR. Based on these findings, Formula IV, which exhibited the lowest amylopectin content and optimal quality characteristics, has been selected for further analysis.

Table 2
Percentage of Amylum, Amylose, and Amylopectin in four experimental analogue rice formulas

Formula	Amylum (%)	Amylose (%)	Amylopectin (%)
I	71.63 a[z]	29.87 a	41.76 a
II	64.99 b	27.07 a	37.92 b
III	60.70 b	25.55 a	34.52 b
IV	54.92 c	24.91 a	30.01 c

Note. [Z]Mean within a column followed by a different alphabet is significantly different at $p \leq 0.05$ using the LSD test

Proximate Analysis

This analysis ascertains the chemical composition of the AR produced using Formula IV by comparing IK to potato and the AR to CAR. Table 3 highlights key findings from the analysis. IK was found to have a higher crude fibre content (6.22%) compared to potato (4.55%), while potatoes exhibited significantly higher carbohydrate content (92.80%) than IK (73.58%). These characteristics suggest that producing AR using Formula IV would result in a product rich in both dietary fibre and carbohydrates, aligning with the attributes of nutritious food. Additionally, the level of calcium oxalate, a compound responsible for causing itching, was significantly reduced after immersion in a 4% NaCl solution for 48 hours. This reduction underscores the importance of addressing chemical constituents like oxalates during food processing. Factors such as cultivar, geographic location, plant maturity, and environmental conditions play critical roles in influencing oxalate levels (Chisenga et al., 2019), emphasising the need for a comprehensive understanding of these variables to optimise food safety and quality.

Table 3 presents the results of the analysis. In this table, we see that:

1. IK has a greater amount of crude fibre compared to the potato. Conversely, potatoes have a higher amount of carbohydrate content compared to IK. More specifically, the fibre content of IK is 6.22%, and that of potato is 4.55%. Meanwhile, the carbohydrate content in potato is 92.80%, much higher than the 73.58% in IK. Thus, if AR is produced using Formula IV, it will yield a substantial amount of dietary fibre and carbs. This is an exemplary characteristic of nutritious food.
2. The level of calcium oxalate, which is responsible for itching, fell dramatically when the subjects were immersed in a 4% NaCl solution for 48 hours.

Particular emphasis is placed on oxalate content. In food processing, it is crucial to comprehend the elements that influence chemical constituents like oxalates, as many factors influence oxalate content, including cultivar, geographic location, plant maturity, and environmental conditions (Chisenga et al., 2019).

Table 3
Chemical composition (in percent) of IK, potato, AR, and CAR

Object	Water	Ash	Protein	Fat	Carbohydrate	Crude Fibre	Ca-oxalate	Calcium
IK	8.84 b	8.72 a	3.05 c	0.23 d	73.58 b	6.22 a	3.21 a	1.89 a
Potato	3.71 d	2.50 c	2.20 d	1.16 c	92.80 a	4.55 c	0.80 b	0.38 c
AR	11.80 a	5.06 b	6.18 a	1.91 b	75.00 b	5.34 b	0.88 b	1.53 b
CAR	7.56 c	2.88 d	4.80 b	2.20 a	82.95 ab	4.30 c	0.65 b	1.66 b

One method to mitigate the impact of oxalates is through the cooking process (Hang et al., 2013). However, in this research instead of using boiling and fermenting methods to decrease the ca-oxalate level, the IK tubers were instead soaked in a NaCl solution of 4% concentration (or 40 gramme (g)/litre (lt)) for a duration of 48 hours. The outcome was highly significant, whereby the ca-oxalate concentration in the soaked tubers was 315 parts per million (ppm), whereas in the control (non-soaked) tubers it was 1000 ppm.

Meanwhile, while the generalised conclusion of (Hasbullah et al., 2023) was that the quality of AR produced using extruders is contingent upon the composition of the raw materials, this research goes further by coming up with a specific composition formula. The significant contribution of this research lies in the development of Formula IV, where the combined dietary fibre content of the AR produced is 35.10%, an amount far greater than the threshold value of 6% for food to be considered a source of fibre (Valencia & Purwanto, 2020).

Physical Characteristics Analysis

A crucial aspect of AR is its physical attributes, such as brightness level (whiteness scale) and the amount of sulphite residue. To measure these attributes, a physical characteristic analysis was conducted, and the findings are presented in Table 4.

As shown in Table 4, the amount of sulphite remaining in the AR was less than 3 ppm, which is the maximum allowable limit (Cuenca et al., 2008). However, in terms of the whiteness scale, the AR produced using Formula IV has a whiteness scale of 46.20%, which is numerically lower than the natural hue of white rice, which is 63.87 percent. The NaCl residue (0.93%) was also still high, perhaps due to the immersion treatment in the production process of the IK flour. Further investigation is required to reduce this residue.

Rapid Viscosity Analysis

The RVA analysis is to determine viscosity changes caused by temperature treatment. Here we summarise the viscosity profiles of the AR and CAR, together with the speed spindle. The findings show that CAR required a maximum duration of 130 seconds and a thickening or gelatinisation temperature of 63.5 °C. However, at a thickening temperature of 69.7 °C, the peak time required for the AR was higher than that for CAR, i.e., 159 seconds. These results suggest that the heating time for starch paste in CAR is lower compared to that in the AR. The deceleration of the coagulation process in CAR led to delayed attainment of maximum viscosity.

Gelatinisation temperature refers to the specific temperature at which the viscosity of a substance increases as a result of the starch granules expanding. An increase in gelatinisation temperature signifies that the starch requires lengthier cooking duration and a higher amount of thermal energy. Consequently, the higher the gelatinisation temperature, the more stable the starch molecular crystals. This research shows that CAR requires more cooking time and thus more energy.

As mentioned in Moorthy (2002), when starch granules are heated above the gelatinisation temperature in the presence of water, they absorb a significant quantity of water and increase in size many times compared to their initial size. These findings are summarised in Table 5.

In Table 5, we see evidence of the viscosity of the AR produced using Formula IV, whether cold paste viscosity (CVP), viscosity beginning plateau (VBP) or viscosity end plateau (VEP), they were all significantly lower for the AR compared to CAR. Since VEP reflects starch's capacity to create a dense paste or gel after undergoing heating and chilling (Ashri et al., 2014), it is seen that CAR generated starch granules of greater size compared to AR, as intended. This indicates that the quality of the AR produced using Formula IV is as desired.

Table 4
Results from physical characteristic analysis

Object of Study	Sulphite (ppm)	Whiteness Scale (%)	Thickness (ºE)	NaCl Residue (%)
AR	2.30 b	46.20 a	1.57 b	0.93 a
CAR	2.80 a	38.30 b	2.11 a	0.53 b

Table 5
Results issued from RVA

Object of Study	PT: Temperature (°C) at 20cP	PT: Time (s) at 20cP	Cold Paste Viscosity (cP)	Viscosity Beginning Plateau (cP)	Viscosity End Plateau (cP)
AR	69.75 a	159.50 a	1618.00 b	135.00 b	475.50 b
CAR	63.50 a	129.50 b	4227.00 a	700.00 a	1673.00 a

Note. cP = centipoise; PT = Past Time

Further, flavour is predominantly influenced by amylose and amylopectin, two components which play a crucial role in the formation of granules. Specifically, the lower the amylose or amylopectin content, the more significant the swelling capacity and thus the better the quality of the AR. As seen in Table 2, the lower amylose and amylopectin content was from Formula IV. Moreover, as can be seen in Table 5, statistical analysis using ANOVA shows that:

1. AR required a higher temperature (69.75 °C) than CAR (63.50 °C) (shown in the first column).
2. AR required a longer duration (159.50 seconds) than CAR (129.50 seconds) (refer to column 2).
3. The cold paste viscosity (CPV), also called the coefficient of apparent viscosity, of the AR was significantly lower (1618.00 cP) than that of CAR (4227.00 cP). The VBP of the AR was also lower (135.00 cP) than that of CAR (700.00 cP).

Whiteness Degree Analysis

The results are presented in Table 6. Further analysis using ANOVA reveals that at 5% significance level, there is a significant difference between the whiteness level of the AR and that of PR. This is another important finding of this research. The disparity in percentages (40.10% for PR and 32.07% for AR) can be attributed to the light brown colour of the IK flour. In fact, the whiteness index of the AR is entirely dependent upon the whiteness index of the IK chips. The heating during the extrusion process can cause gelatinisation of the carbohydrate ingredients, which may reduce the whiteness level of the analogue rice product (Amalia et al., 2020).

Table 6
Whiteness degree (%) of PR and AR

Component	Whiteness
PR	40.10 a
AR	32.07 b

FT-IR Analysis

In this research, the functional groups of the AR produced using Formula IV were examined using FT-IR analysis. Then, as a comparison, that of IK, potato, CAR and PR were also examined. It is expected that functional groups with similar characteristics will exhibit the same chemical reactions. The graphical results are displayed in Figure 1, while the numerical results are shown in Table 7.

Figure 1 shows that, in terms of absorbance (in %) with respect to wave number (in cm^{-1}), the pattern for IK is the same as that for potato, AR, CAR, and PR. The numerical data in Table 7 adds weight to the patterns shown in Figure 1.

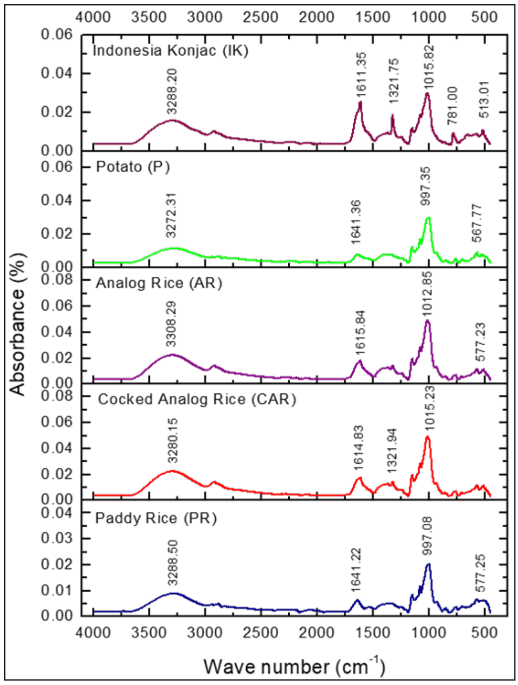

Figure 1. FT-IR spectra of IK, potato, AR, CAR, and PR (top to bottom)

Microstructure Profile Analysis

In order to analyse the microstructure of both the AR and CAR, the scanning electron microscope (SEM Philips XL30) and the image was taken at an acceleration potential of 20 kV was employed. Examination was at a magnification, which enabled accurate determination of the presence of porosity and starch granules. The results are displayed in Figure 2: (a) microstructure profile for AR, and (b) for that of CAR. This figure illustrates the contrasting visual characteristics of AR and CAR with regard to porosity and gelatinisation (Ashri et al., 2014).

The results suggest that the gelatinisation of the AR and CAR led to starch degradation and retrogradation. Additionally, unlike the AR, the character of CAR shifted to a high porosity level, which means that it became absorbent. This strengthens the findings of (Mendoza et al., 2012).

CONCLUSION

In the attempt to produce high-quality AR, this research came up with Formula IV, which gives the optimal composition of IK flour, potato flour, sago, GMS, and water. The formula IV on the best composition were: Indonesia konjac (39,50 %), *S. tuberosum* or potato (19,50 %), sago (9,50 %), glyceryl monostearate (GSM) (2,00 %), and water (29,50 %).

Table 7
Numerical results in terms of wavelength (cm^{-1}) and vibration type

PR		CAR		AR	
Wavelength	**Vibration Type**	**Wavelength**	**Vibration Type**	**Wavelength**	**Vibration Type**
577.25	CH bend bonded	-	-	577.24	CH bend bonded
997.08	C-O-C stretch	1015.23	C-O-C stretch	1012.85	C-O-C stretch
1641.22	C=C stretch, C=O stretch	1614.83	C=C stretch, C=O stretch	1615.8	C=C stretch, C=O stretch
3288.50	OH stretch, H-bonded	3280.15	OH stretch, H-bonded	3308.29	OH stretch, H-bonded

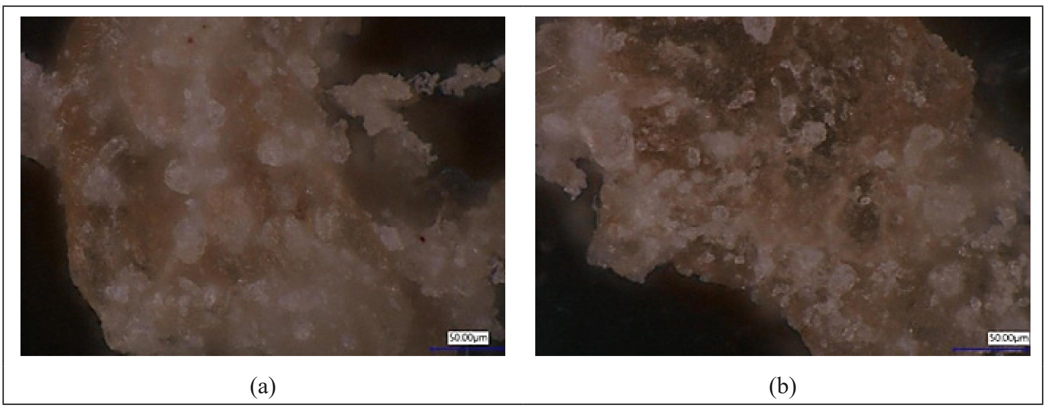

Figure 2. Microstructure profile of (a) AR and that of (b) CAR

The AR produced using this formula (IV) has been achieved and can be categorised as a dietary food, which is an important discovery.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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