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Impact of natural aging on the physical and pasting properties of Indonesian Ciherang rice during storage

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ABSTRACT

Natural aging induces substantial variations in the properties of rice during extended storage periods. This study compared the changes in the texture and paste profile of local Indonesian Ciherang rice varieties stored at room temperature for 0, 12, 24, 36, and 48 months. Texture Profile Analysis (TPA), Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and Rapid Visco Analysis (RVA) were used to compare the changes in texture, structure, and pasting characteristics. The TPA results showed an increasing trend in hardness, cohesiveness, springiness, and chewiness, indicating starch retrogradation and enhanced intermolecular interactions. FTIR spectra revealed decreased intensities of –OH and carbonyl groups, indicating water loss and the degradation of lipid/protein molecules. XRD confirmed the retention of A-type crystallinity without polymorphic transformation, indicating morphological stability despite prolonged storage periods. The RVA profile demonstrated a reduction in peak and breakdown values and an overall increase in the setback and final viscosities up to 24 months, reflecting the high retrogradation and reduced water absorption capacity of the samples. The reduction in final viscosity at 36 months indicated molecular breakdown and a less stable gel network. Overall, long-term atmospheric storage qualitatively alters the texture and viscoelasticity of rice. These findings underscore the importance of monitoring rice aging to improve storage strategies, optimize industrial processing, and ensure consumer acceptance of aged rice products.

Contribution/Originality: This study contributes to the integrated analysis of the structural, textural, and pasting properties of long-term natural aging of Indonesian Ciherang rice under tropical storage. Using TPA, FTIR, XRD, and RVA, the findings show that deterioration accelerates after 24–36 months, with implications for storage management and consumer acceptance.

1. INTRODUCTION

Rice (Oryza sativa L.) is a food staple for more than half the people in the world, and in Indonesia, it is the basis of national food security (Sen, Chakraborty, & Kalita, 2020). Much of it is stored for long periods as government inventories maintained by Bulog, making it an ideal system that serves as a model for studying quality changes due to storage. Therefore, understanding the impact of storage on rice quality is crucial, not only for consumer acceptability but also for national food stock stability.

Rice spontaneously ages during storage and alters its physicochemical characteristics (Hati, Karyadi, & Bintoro, 2023), texture (Ding et al., 2023), and pasting properties (Shi et al., 2022). These are primarily attributed to starch retrogradation (Denchai et al., 2019; Ding, Zhang, Tan, Fu, & Huang, 2019), water redistribution (Sultana, Faruque, & Islam, 2022), and readjustment of structures (Shi et al., 2022), which all affect the processing quality and palatability of rice products. Despite some research on aging, the studies were restricted to short-term storage or employed accelerated storage conditions, such as high temperature or conditioned humidity (Millati, Pranoto, Utami, & Bintoro, 2021; Wang et al., 2021; Zhao et al., 2021). However, such experiments might not be able to fully reproduce the entire dynamics of rice aged for long periods in real tropical situations.

Therefore, this study examined the natural aging process of Indonesian Ciherang rice over an extended period under typical tropical conditions. Ciherang was selected because it is one of the most widely distributed varieties in Indonesia, representing the practical realities of government stock management (Sitaresmi et al., 2023). By integrating texture profile analysis (TPA), Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and Rapid Visco Analysis (RVA), this study provides a comprehensive evaluation of the structural, textural, and pasting changes during prolonged storage. The findings are expected to inform rice storage policies, industrial processing strategies, and consumer-oriented product developments.

To our knowledge, this is one of the few studies that systematically investigated rice stored for up to 48 months under natural tropical conditions. By situating the analysis within the context of government-managed reserves, this study contributes novel insights that extend beyond laboratory simulations, offering practical value for both academic research and food security applications. This study aimed to examine the long-term (up to 48 months) natural aging of Indonesian Ciherang rice under tropical conditions and its implications for storage management and product quality.

2. METHODS

2.1. Materials and Sampel Preparation

The primary material used was locally grown rice (Ciherang variety) procured from the Bulog Cirebon Warehouse, West Java Regional Division, Indonesia. The milled rice was packaged in sealed woven plastic bags at ambient conditions (31.3 ± 0.9°C and 58 ± 6.5% RH) and stored for 12, 24, 36, and 48 months. The control (0 month) was freshly harvested rice. Each sample (1 kg) was randomly selected for analysis. Except for the TPA, each rice sample was milled using a laboratory-scale pulverizer to obtain fine, white rice flour. The flour was then sieved with a 100-mesh Sieve Shaker (Retsch, Germany) and stored in a container before testing.

2.2. Texture Profile

Texture profile analysis (TPA) was determined using a Texture Analyzer (TA-XT Plus, Stable Microsystems, UK) (Tao, Yu, Prakash, & Gilbert, 2020). Rice was cooked using an automatic rice cooker (Miyako, Indonesia) with a 1:1.6 water-to-rice ratio. The cooked rice was allowed to cool at the warm setting for 10 minutes. The uppermost layer and rice adhering to the sides of the rice cooker were then removed. After being gently stirred, the cooked rice was taken out of the rice cooker and placed in a covered pot at room temperature. The TPA settings used a P/36R probe. The pre-test and test speeds were both 0.5 mm/s. The speed after testing was 2 mm/s, with a spacing of 10 mm. The strain reached 90%, and the trigger force measured 5.1 g.

2.3. FTIR Spectrum Analysis

The functional groups were identified using FTIR (Nicolet iS10, Thermo Scientific, MA, USA) (Hu et al., 2022). Rice flour was combined with KBr at a 1:100 ratio and subsequently compressed into a pellet form. Spectral measurements were taken from 4000 to 500 cm^{-1}, with a resolution of 4 cm^{-1}.

2.4. Pasting Properties

The pasting properties were determined using an RVA 450 machine from Newport Scientific, Australia (Nakamura, Katsura, Maruyama, & Ohtsubo, 2021). Flour (3.5 g) was mixed with 25 ml of demineralized water and analyzed using a hold cycle of 50–95°C, after which it was cooled to 50°C. The observed parameters were pasting temperature, peak, breakdown, setback, and final viscosities.

2.5. XRD Analysis

The crystal configurations of the rice samples were determined using XRD (PANalytical Aeris, Malvern, UK) (Taguchi et al., 2023). Rice flour was tested with Cu Kα light (λ = 1.5406 Å), at 15 mA, 40 kV, 2θ = 10–30°, and a rotation time of 1.0 s.

2.6. Statistical Analysis

Texture profile analysis was conducted ten times, whereas paste profile analysis was carried out three times. FTIR and XRD data were obtained in triplicate. Data were analyzed using ANOVA, followed by Tukey's HSD or Games–Howell test ($\alpha = 0.05$), depending on variance homogeneity. All statistical analyses were performed using IBM SPSS Statistics (version 26.0). FTIR and XRD data were visualized using Origin (OriginLab Corporation, USA).

3. RESULTS AND DISCUSSION

3.1. Texture Profile

Texture profile analysis (TPA) of Ciherang rice during storage revealed significant changes in hardness, adhesiveness, cohesiveness, springiness, and chewiness (Table 1). The hardness values increased markedly with storage duration, indicating progressive textural changes in rice during aging (Table 1).

At 0 months, hardness was 1143.51 gf, which is the freshly milled texture of rice. At 12 months, there was a slight increase in hardness but not statistically significant ($P < 0.05$), which reflects that the first half of the storage period was of little contribution to grain stiffness.

However, at 24 months, the hardness significantly increased, indicating the onset of widespread starch retrogradation and crystallization. The upward trend continued at 36 months, which was significantly higher than in the previous stages.

Finally, at 48 months, the hardness surged to 4211.08 gf, nearly four times the initial value, representing the most pronounced structural stiffening of the rice. Jungtheerapanich, Tananuwong, and Anuntagool (2017) also reported the increase in hardness and a decrease in adhesiveness for rice that had been stored for 18 months at 30°C. This observation suggests an enhancement in the starch gel structure attributable to amylose retrogradation during storage (Chakraborty, Govindaraju, Kunnel, Managuli, & Mazumder, 2023). This increase in hardness can also be attributed to the reduction in free moisture and increased intermolecular interactions within the rice matrix. Yan, Lu, and Gui (2021) revealed that the increase in rice hardness was probably due to the cross-linking of short-chain amylose within starch granules.

Table 1. Texture profile analysis of Bulog rice (Ciherang variety) with various storage periods.

Storage period (Month)	Parameter				
	Hardness (gf)	Adhesiveness (gf.s)	Cohesiveness	Springiness (%)	Chewiness (gf)
0	1143.51 ± 141.31^{a}	-50.29 ± 7.14^{a}	0.34 ± 0.02^{a}	0.36 ± 0.02^{a}	172.91 ± 26.78^{a}
12	1377.28 ± 116.66^{a}	-57.87 ± 9.43^{a}	0.37 ± 0.03^{a}	0.40 ± 0.03^{a}	274.82 ± 44.90^{a}
24	1961.22 ± 232.18^{b}	-75.65 ± 15.66^{a}	0.41 ± 0.03^{b}	0.51 ± 0.05^{b}	323.50 ± 47.04^{b}
36	2422.66 ± 176.70^{c}	-91.68 ± 12.01^{a}	0.42 ± 0.02^{b}	0.59 ± 0.08^{b}	620.70 ± 80.94^{b}
48	4211.08 ± 303.89^{d}	-234.14 ± 28.64^{b}	0.48 ± 0.03^{c}	0.71 ± 0.05^{c}	1425.60 ± 196.03^{c}

Note: Data are expressed as mean ± standard deviation. The letters a, b, c, and d indicate the grouping results of the multiple comparison test. Values that share the same letter are not significantly different from each other at $P < 0.05$, according to Tukey's HSD test.

Adhesiveness, which represents the stickiness of cooked rice, showed a declining trend with increasing storage duration (Table 1). The statistics demonstrate that adhesiveness remains relatively stable during the first three years of storage ($P < 0.05$), with no significant changes, but deteriorates drastically in the fourth year. This indicates that adhesiveness is less sensitive to early retrogradation than hardness, but is severely affected by extended storage. The adhesiveness of stored rice is due to changes in its composition during storage. Yan et al. (2021) reported that storing rice at 35℃ for 200 days made it harder and less sticky. Saikrishna, Dutta, Subramanian, Moses, and Anandharamakrishnan (2018) also stated that the texture of the cooked aged rice was harder and less sticky compared with freshly harvested rice. The observed reduction in adhesiveness indicates a decrease in the stickiness of cooked rice. This phenomenon is likely attributable to the degradation of amorphous starch and a reduction in soluble components, which typically contribute to surface tackiness (Yanxia, Xianqing, & Yurong, 2018).

Cohesiveness, which reflects the internal bonding strength of the rice structure during mastication, increased progressively with storage duration (Table 1). Cohesiveness increased slightly but was not different from fresh rice ($P < 0.05$) between 0 and 12 months, indicating the initial year of storage did not significantly alter the structural integrity internally. It increased significantly from 24 months through 36 months. The value was statistically equal, however, which indicated the stabilization of the trend. Lastly, at 48 months, cohesiveness achieved its peak value, which differed significantly from all the earlier stages, indicating the peak strengthening of the rice matrix. Statistical analysis identified three stages: stability in the first year, a sharp increase between 12 and 24 months, and peak reinforcement at 48 months. The trend concurs with the gradual rearrangement of starch molecules into more ordered crystalline domains that reinforce the structural strength of the cooked rice. Rahman, Al Attabi, Al-Habsi, and Al-Khusaibi (2021) stated that cohesiveness is a textural property that indicates the degree to which a sample maintains its integrity during chewing.

Springiness, or the extent to which rice springs back to its initial form after being pressed, increased steadily with storage duration (Table 1). At 0 months, springiness exhibited moderately high elasticity typical of fresh-milled rice. After 12 months, it increased slightly, with no significant difference compared to fresh rice, suggesting that early storage did not markedly alter elasticity. By 24 months, springiness increased, but was statistically similar to that at 36 months, indicating stabilization of elastic strengthening, which significantly reflects enhanced resilience due to starch retrogradation. At 48 months, springiness was significantly higher than at all earlier stages, showing maximum elasticity in long-term stored rice. The results provide evidence of three phases: balance during the first year, intense reinforcement between 12 and 24 months, and maximum reinforcement at 48 months. This indicates that the molecular ordering of starch into more crystalline and hydrogen-bonded units progressively reinforces the rice matrix (Chen, Zhao, Li, & Chen, 2024).

The chewiness parameter also showed significant increases, supporting the hypothesis that aging causes rice to become chewier and requires greater chewing effort. Park, Kim, Park, and Kim (2012) reported that storage at elevated temperatures resulted in increased cohesiveness and hardness compared with storage at cooler temperatures.

The TPA results showed a consistent increase in hardness, cohesiveness, springiness, and chewiness with storage duration. This change occurred starting from 24 months of storage, which was significantly different from 12 months of storage ($P < 0.05$). This indicates the progressive retrogradation of starch, especially amylose, which forms tighter gel networks and increases resistance to deformation (Kim et al., 2015). Similar increases in hardness were observed due to hydrogen bond formation and the realignment of short-chain amylose, making the rice texture firmer and less adhesive (Chakraborty et al., 2023; Yan et al., 2021).

3.2. FTIR Spectra

FTIR spectra were utilized to identify the functional groups C-H, C=O, and O-H, which serve as indicators of various molecular components and their interactions. Figure 1 shows the FTIR spectra of Bulog rice flour at 0, 12, 24, 36, and 48 months of storage, showing no changes in the main functional groups in the main bands (–OH, –CH, and –C=O). Nevertheless, the intensity of the –OH band (3200–3400 cm^{-1}) exhibited a tendency to diminish with prolonged storage duration, suggesting a weakening of hydrogen bonds in the water. The spectral bands observed in the range of 3,000–3,500 cm^{-1} are indicative of the O-H stretching vibration regions (Lohumi et al., 2014). This supports the hypothesis that free water molecules are released during storage, accelerating retrogradation (Chakraborty et al., 2023). Hydrogen bonding is the primary driver of retrogradation (Lu, Ma, Chang, & Tian, 2021). The retrogradation is influenced by changes in the distribution of amylose in starch molecules (Li, Hu, & Li, 2021). Carbonyl bands (~1600–1700 cm^{-1}) associated with lipids and proteins also exhibited a decrease in intensity (Zhang et al., 2025), indicating the degradation of these molecules due to oxidation or hydrolysis during storage (Hu et al., 2022; Rashid, Liu, Han, & Jatoi, 2022; Wang et al., 2022). The spectral bands observed between 400 cm^{-1} and 700 cm^{-1} are indicative of the structural vibrations associated with amylopectin and amylose (Flores-Morales, Jiménez-Estrada, & Mora-Escobedo, 2012; Oppong, Panpipat, & Chaijan, 2021). Additionally, the spectral band at 500-800 cm^{-1} corresponds to the region of C-OH bending, whereas the C=O group was observed at 1000-1700 cm^{-1}.

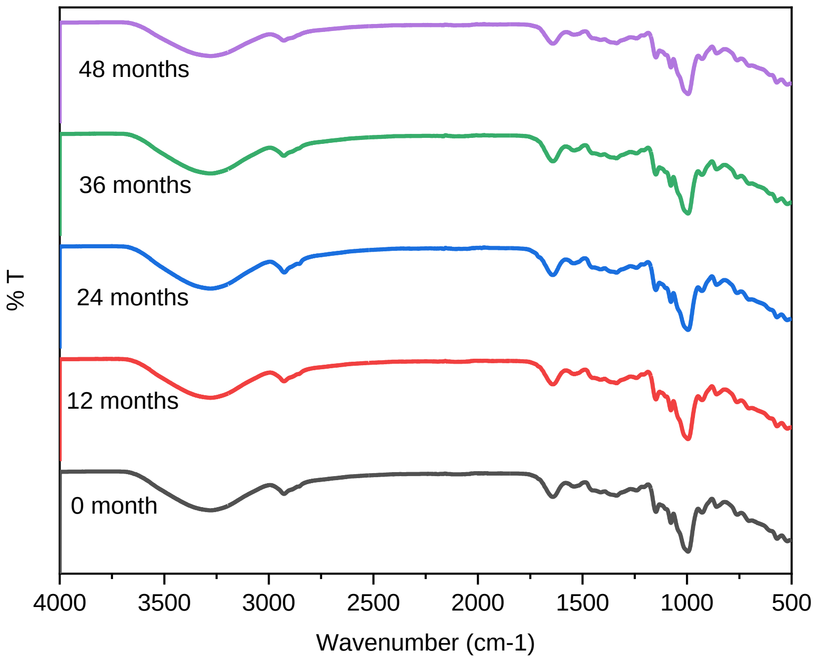

Figure 1. FTIR spectra of Bulog rice flour (Ciherang variety) at various storage periods.

3.3. Pasting Properties

Rice flour pasting temperature (PT) increased progressively during storage from 80.97°C at 0 months to 85.30°C at 36 months, then declined thereafter to 84.54°C at 48 months (Table 2). Statistical grouping indicated that PT values between 0 and 12 months were not significantly different ($P < 0.05$), implying that the changes within the initial year of storage were relatively minor. However, significant increases occurred at 24 and 36 months, indicating that long-term storage renders starch granules resistant to gelatinization. The decrease at 48 months was negligible and not significantly different from that at 36 months. The increase in PT could result from crystalline reorganization and stronger amylose–lipid complexes that require more energy to gelatinize (Nakamura et al., 2021; Shi et al., 2022).

Peak viscosity (PV) values showed a clear declining trend with longer storage durations (Table 2). At 0 months, PV was highest at 4436.67 cP, indicating the strong swelling capacity of starch granules during heating. After 12 months, the PV decreased significantly ($P < 0.05$), showing the first major reduction in swelling ability. A further significant decline occurred at 24 months and 36 months. However, after 36 months, PV did not experience a significant decline ($P < 0.05$) until 48 months, suggesting that the decline had reached a stable phase. (Hu et al., 2022) stated that the decline in PV is primarily attributed to the retrogradation and molecular rearrangements of starch polymers. During storage, amylopectin undergoes recrystallization, and amylose-lipid complexes become more stabilized, both of which limit the granules' ability to absorb water and swell (Garofalo, Salazar, Palacios-Ponce, Cornejo, & Corradini, 2024). Zhang et al. (2025) reported that the interaction between proteins and starch may have prevented the starch particles from expanding, resulting in a decrease in PV. Whereas Yang et al. (2020) stated that rice with higher peak viscosity has better eating quality. Functionally, a lower PV means that aged rice produces a thinner paste upon cooking, which negatively affects processing properties such as thickening and gelling capacity. This has direct implications for consumer perception, as rice with lower PV tends to produce harder, less sticky cooked grains (Giau, Van Hao, Van Tai, Minh, & Thuy, 2024; Sharma et al., 2024).

The breakdown viscosity (BD) showed a consistent and significant decline during storage (Table 2). At 0 months, BD was 2385.00 cP, indicating high granule swelling and subsequent structural fragility during heating. After 12 months, the BD decreased significantly to 1927.00 cP, suggesting the onset of reduced swelling stability. At 24 months, BD dropped further to 1298.00 cP, confirming the substantial loss in the capacity of starch granules to withstand shear and heat.

The BD experienced a progressive and significant decline up to 36 months, beyond which no further significant reductions were observed. Storage of indica rice (Zhongzheyou 8) for 2 years at a temperature of 20–25°C also showed a decrease in PV and BD (Hu et al., 2022). Functionally, reduced BD has direct implications for the cooking and processing quality of rice. Rice with a lower BD tends to produce firmer and less tender cooked grains. For industrial applications, the loss of swelling power diminishes the thickening ability, limiting the suitability of aged rice for products that rely on paste viscosity (Borah, Das, Mukhopadhyay, & Mahanta, 2023).

Setback viscosity (SV) increased markedly ($P < 0.05$) from 0 months to 24 months, indicating enhanced amylose retrogradation and a firmer texture in cooled rice. After 24 months, the SV declined significantly ($P < 0.05$), suggesting that retrogradation dominates within the first two years, whereas prolonged storage leads to starch degradation, reducing the capacity for reassociation.

Functionally, a higher SV in mid-storage rice corresponds to undesirable hardness, whereas a later decline reflects molecular breakdown rather than quality recovery. The final viscosity (FV) increased significantly from 0 to 24 months, indicating stronger gel formation owing to starch retrogradation. Beyond this point, the FV declined at 36 months and returned to baseline at 48 months, suggesting starch depolymerization and molecular breakdown. Functionally, a higher FV during mid-storage leads to firmer cooked rice, whereas a later decline indicates a loss of structural integrity rather than an improvement in quality (Zhou, Robards, Helliwell, & Blanchard, 2003). Katekhong and Charoenrein (2012) stated that there was a decrease in PV and BD but an increase in FV, SV, and PT for Khao Dawk Mali 105 rice variety stored at a temperature of (25 ± 2°C) for 12 months. Guo et al. (2017) reported that storing Japonica rice at a temperature of 45°C for 6 months caused a decrease in PV and BD but increased SV and FV.

Table 2. Pasta profile of Bulog rice flour (Ciherang variety) stored for various durations.

Storage duration (Month)	Parameter				
	PT	PV	BD	SV	FV
0	80.97 ± 1.98^{a}	4436.67 ± 15.04^{a}	2385.00 ± 30.81^{a}	2015.67 ± 107.13^{a}	4100.67 ± 8.08^{a}
12	$82.35 \pm 0.06^{a,b}$	4086.50 ± 184.59^{b}	1927.00 ± 119.63^{b}	3013.00 ± 179.26^{b}	5172.50 ± 184.94^{b}
24	$84.50 \pm 0.44^{b,c}$	3622.33 ± 34.82^{c}	1298.00 ± 100.73^{c}	3252.67 ± 152.92^{b}	5577.00 ± 54.56^{c}
36	85.30 ± 0.95^{c}	2948.33 ± 119.83^{d}	916.67 ± 153.873^{d}	2544.00 ± 204.63^{c}	4575.67 ± 238.62^{c}
48	84.54 ± 0.44^{c}	2929.33 ± 58.62^{d}	991.67 ± 25.48^{d}	$2182.67 \pm 37.82^{a,c}$	4120.33 ± 121.83^{a}

Note: PT: pasting temperature; PV: peak viscosity; BD: breakdown viscosity; SV: setback viscosity; FV: final viscosity. Data are expressed as mean ± standard deviation. The letters a, b, c, and d indicate the grouping results of the multiple comparison test. Values that share the same letter are not significantly different from each other at $P < 0.05$, according to Tukey's HSD test.

3.4. Crystallinity Pattern

The X-ray diffraction patterns of rice flour across the five storage durations consistently exhibited A-type crystallinity, with strong diffraction peaks at 2θ angles of 15°, 17°, 18°, and 23° (Figure 2). This pattern is typical of cereal starches and remained unchanged throughout the 48-month period, indicating no polymorphic transition to the B- or C-type structures (Cornejo-Ramírez et al., 2018; Guo, Zhang, Bian, Cao, & Wei, 2020; Nagataki, Tomita, Himeda, Takemori, & Fukuoka, 2018; Oh et al., 2024).

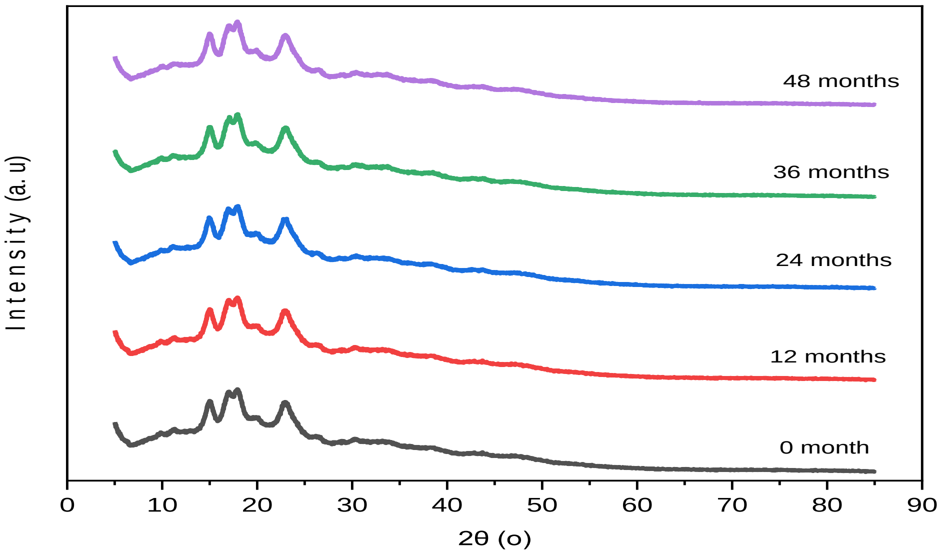

Figure 2. X-ray diffraction (XRD) patterns of Bulog rice flour (Ciherang variety) at various storage periods.

While the crystalline structure was retained, slight increases in diffraction intensity were observed over time, which may be linked to the enhanced retrogradation and ordering of amylose chains. These results suggest that natural aging under tropical ambient conditions does not disrupt the macromolecular architecture of rice flour. Instead, it promotes subtle reorganization within the existing crystalline framework, contributing to the observed increases in texture firmness, pasting temperature, and reduced peak viscosity (Gu et al., 2019; Nagataki et al., 2018).

4. CONCLUSION

Natural aging was found to have a significant influence on the physical and paste properties of rice flour during storage times longer than short-term. Texture changes, such as increased hardness, cohesiveness, and chewiness, can be attributed to starch retrogradation and moisture redistribution within the matrix. FTIR analyses confirmed molecular-scale changes, indicated by reduced hydroxyl and carbonyl absorption, reflecting inadequate water-binding functionality and structural reorganization of the starch granules. Despite these molecular-level changes, XRD analysis revealed that the crystalline structure of rice starch remained predominantly A-type, indicating its macrostructural integrity. RVA patterns showed a reduction in peak and breakdown viscosities, along with an increased setback viscosity, which reflects reduced granule swelling and enhanced retrogradation starch formation.

From a technological and industrial perspective, these findings have important implications for rice storage and processing. These results highlight the need to carefully monitor storage duration in government stockpiles and adapt processing strategies to produce rice-based products of consistent quality. The evidence that quality deterioration accelerates after 24–36 months provides practical guidelines for stock management under tropical conditions. Future studies should incorporate consumer sensory evaluations to validate acceptability thresholds and explore metabolomic profiling to better understand biochemical changes in aged rice. Such approaches would complement the present findings and further support the development of storage policies and innovative rice-based products.

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