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Research Article

MALTING CHARACTERISTICS, NUTRITIONAL PROFILING, ANTIOXIDANT ACTIVITY AND STRUCTURAL PROPERTIES OF DIFFERENT MALTED CEREALS

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Abstract

This study examined the effect of malting process on malting properties, nutritional profiling, antioxidant activity, and structural features of different cereals and their use in brewing process. Grains were steeped, germinated, and kilned with analytical measurements being made on unmalted (day 0) and malted (day 6). There was a significant ($p \leq 0.05$) improvement in the cereals characteristics after malting process. Germination rates (88.33-98.00%), malting yields (77.00-79.67%), diastatic power (37.66-134.97DP) and alpha amylase activity (75.14-149.81CU/g) were increased and a decrease in phytic acid content (29-48). Proximate composition showed that moisture content (5.03-5.90%), crude protein (4-25%) and crude fat (6-11%) was decreased in all cereals while increase in the percentage of ash (10%), crude fiber (3-17%) and nitrogen free extract (11-12%). Phytochemical evaluation showed high total phenolic measure (37-57 and 169.36-220.76 mg gallic acid equivalent (GAE) 100g-1, total flavonoid measure (65-115 and 58.94-104.02 mg quercetin (QE) 100 g -1), DPPH radical scavenging activity (50-106 and 57.57-70.13 percent) and Fourier-transform infrared (FTIR) spectra showed modifications in the structure of the carbohydrate and protein presumably due to enzymatic hydrolysis. Barley showed better improvements in terms of the enzymatic and antioxidant parameters, while on the other hand, the anti-nutrients and the increases in bioactive compounds were significant in corn and rice. These results highlighted the malting as a viable bioprocessing technique to increase the nutritional properties, digestibility and function of cereals to be applied in food, with application of minor cereals as an adjunct in brewing process.

1. Introduction

Cereal grains and cereal based products provide a balanced source of energy, carbohydrates, proteins, fiber and essential micronutrients - including vitamin E, vitamin B, zinc and magnesium (Garg et al., 2021). Cereal products have proven their potential efficiency in reducing chronic conditions, including cardiovascular disorders, diabetes, and colorectal cancer (Pasha et al., 2020). Cereals such as wheat, rice, corn, barley, sorghum, millet, and oats occupy about three-fourths of the world's arable land, underscoring their critical role in global agriculture and land use (Guo et al., 2020). The expansion of cereal cultivation has also raised concerns about sustainability, including water usage, soil degradation, and the impact of climate change on yields, prompting calls for more resilient farming practices (FAO, 2025).

Barley is a good source of protein, starch, lipids, β-glucan, arabinoxylans, and phenolic acids. Barley contains the amino acid proline, and glutamine-rich protein, e.g., hordein, makes up 40% to 50% of total grain protein (Geng et al., 2022). Rice grains are rich in soluble dietary fiber, β-glucan, polyunsaturated fatty acids, monounsaturated fatty acids, and fat-soluble vitamin E. Corn grains are highly nutritious and contain important nutrients such as phenolic acids, flavonoids, antioxidants, vitamins, minerals, and fiber. These cereals are frequently utilized in chemical production, processing, animal feed, and industrial applications such fillers and absorbents (Rosentrater and Evers, 2018). Grits and whole, malted cereals are used as adjuncts in the preparation of beer (Cadenas et al., 2021).

Malting, a controlled germination process involving steeping, germination, and kilning, profoundly impacts the nutritional profile of cereals by activating endogenous enzymes that hydrolyze complex macromolecules and reduce anti-nutritional factors, thereby enhancing digestibility and bioactive content (Luque et al., 2023). In barley, malting reduces macronutrients such as starch (by 8-18 g/100 g dry weight) and total dietary fiber (by 5-7 g/100 g dry weight) due to enzymatic degradation, while significantly increasing gamma-aminobutyric acid (GABA) by 18-124%, free amino acids, phenolic acids (e.g., 3.6-fold increase in cinnamic acid derivatives like ferulic acid), and antioxidant activity as measured by ABTS, DPPH, and FRAP assays (Zhou et al., 2020). Barley components and malting affect malt's overall antioxidant qualities; phenolic compounds and maillard reaction products help scavenge radicals, however some pro-oxidant effects happen at high temperatures (Carvalho et al., 2016). Malting increases TPC and RSA in barley grains and cereals, with kilning enhancing polyphenol formation (Vingrys et al., 2022). Free phenolic extract from malted barley shows hepatoprotective effects, with phenolics peaking at 48 h germination (Wang et al., 2018). Malting reduces vitamin E but maintains or increases antioxidant capacity in barley genotypes (Do et al., 2015).

For rice, the use of a composite malted dark-purple variety results in improved phenolic composition and antioxidant activity of the resulting malt extract with significant effects of the rice cultivar and the malting conditions used on total phenolic content (TPC) and DPPH radical scavenging activity (Vongjullaphat et al, 2021). Malting also increases the concentration of feruloyl arabinoxylans and as such enhances the antioxidant activity (Rao & Muralikrishna, 2006).

For corn, malting significantly increases proteolytic activity (to 0.255 IU), free amino nitrogen (up to 660 mg / 100 g), decreases starch content (from about 23 to 6%), and decreases phytate (to 3 mg/100 g) and oxalate (to 9 mg/100 g) all as a result of malting. These changes enhance protein digestibility, mineral bioavailability and concentration of bioactive compounds (Mbah et al. Moreover, the malting and fermentation processes also provide additional benefits of increasing antioxidant levels in maize (Ogunremi et al., 2022). Blue corn malt in particular increases phenolic content and antioxidant capacity as measured by DPPH radical scavenging (Barba- Pedrero et al. 2021).

Despite of early research on malting of barley there remains a significant research gap

in systematically comparing minor or alternative cereals like corn and rice under identical malting conditions compared to barley. To increase the use of these cereals in brewing adjuncts, enhancing digestibility, mineral bioavailability and anti-nutrient degradation. Therefore, the main objectives of this study were to evaluate the effect of malting on the nutritional profile of the cereals and determination of malting characteristics of the cereals.

2. Materials and Methods

2.1. Procurement of raw materials

Barley, corn and rice were obtained from the Ayub Agricultural Research Institute, Faisalabad, Pakistan. All reagents and chemicals of analytical grade were sourced from Sigma-Aldrich (St. Louis, Missouri, USA) via a local supplier.

2.2. Malting process

The grains were cleaned by the removal of debris and damage grains. Malting process was carried out under an optimized procedure combining steeping, germination and kilning, in order to improve sustainability and operational efficiency (Guimarães et al., 2025). Steeping was carried out in distilled water at the ratio of 2:1 (w/v) with the addition of 0.5% NaOH to ensure antimicrobial control, at the temperature of 25±0.5ºC for a minimum of 24 h, with changing the water after every 8 h to achieve a moisture content of 45-50%. Germination rates occurred within a controlled environment chamber (Memmert ICH 110, Eagle, Wisconsin, USA) under a relative humidity of 90 to 95 and temperature of 18 to 22 for 6-days with daily monitoring. Kilning was done in a hot air oven at a temperature of 55-65ºC for 6-8 h therefore reduced moisture content to 4-6 %. (Kong et al., 2024) The malted products were kept in polyethylene sealed bags at 4ºC before being tested.

2.3. Malt Analysis

2.3.1 Germination Rate

The germination rate was assessed according to the method described by Thanni et al. (2024). Wherein one hundred grains were steeped followed by germination under controlled conditions (16°C and high humidity above 80% for 6 days. The rate was calculated as:

$$\text{Germination rate (\%)} = (\text{Number of germinated grains} / 100) \times 100 \quad (1)$$

2.3.2. Malt Yield

Malt yield was calculated according to the protocol of Guimarães et al. (2025), involving killing of grains to stop the germination process and during of the malt. After that dry weight of the malt was measured and malting yield was calculated as,

Malting yield (%) = (Dry weight of malted grains / Dry weight of original grains) × 100.

2.3.3. Diastatic Power

Diastatic power was measured using a novel automated glucose-specific enzymatic method (AOAC 935.31, 2019). Malt extract (0.5 g in 50 mL buffer) was incubated with starch substrate, and D-glucose formation was quantified colorimetrically at 510 nm using a glucose oxidase-peroxidase kit. Results were expressed in °DP, calibrated against standards.

2.3.4. α-Amylase Activity

The Ceralpha method was used to test the α-amylase activity as described by McCleary et al. (2002; updated in Megazyme kit instructions, 2024). 20 mL of malate buffer were used to extract one gram of ground malt, which was then centrifuged and diluted. Then, 0.2 mL of the extract was mixed with 0.2 mL of blocked p-nitrophenyl maltoheptaoside substrate that had been heated to 40°C for 20 minutes. Absorbance was measured at 405 nm after the process was halted with 1 M tris buffer. CU/g was used to express the activity.

2.4. Phytic Acid

Phytic acid was determined colorimetrically (Haug & Lantzsch, 1983). Sample (1 g) was extracted in 50 mL 0.2 N HCl for 3 hours, centrifuged, and 0.5 mL supernatant reacted with ferric solution in a boiling bath for 30 minutes. After cooling, bipyridine was added, and absorbance measured at 519 nm. Results were expressed as mg/g using a phytate standard curve.

2.5. Proximate Composition

Analyses followed AACC Official Methods (2010). Moisture Content: AACC 925.10. Samples (2 g) dried at 105°C to constant weight; % moisture = weight loss × 100 / initial weight. Crude Protein: AACC 990.03 (Kjeldahl). Digestion with H_2SO_4, distillation, titration; % protein = % N × 6.25. Crude Fat: AOAC 920.39 (Soxhlet). Extraction with petroleum ether; % fat = extract weight × 100 / sample weight. Ash Content: AACC 942.05. Incineration at 550°C; % ash = residue weight × 100 / sample weight. Crude Fiber: AACC 962.09. Sequential acid-alkali digestion, filtration, ashing; % fiber = (dried residue - ash) × 100 / sample weight. NFE: Calculated as 100 - (% moisture + % protein + % fat + % ash + % fiber).

2.6. Phytochemical Profile

2.6.1. Total Phenolic Content (TPC)

TPC was assessed by using the Folin-Ciocalteu method as described by Ogunremi et al., (2022). Where 100 µL of extract was mixed with 0.5 mL of reagent, incubated for 5 minutes, then 1 mL 7.5% Na_2CO_3 was added, diluted to 5 mL with distilled water, after that incubation in the dark for 60 minutes. Absorbance was measured by using spectrophotometer at 765 nm; expressed as mg GAE/100 g.

2.6.2. Total Flavonoid Content (TFC)

TFC was assessed by following the aluminum chloride method as mentioned by Solgajová et al., 2014). 0.5 mL of extract mixed with 0.3 mL 5% $NaNO_2$ for 5 minutes then 0.3 mL of 10% $AlCl_3$, for 6 minutes followed by 2 mL of 1M NaOH and dilution to 10 mL. Absorbance at 510 nm was measured as mg QE/100 g.

2.6.3. DPPH Antioxidant Assay

The 2,2-Diphenyl-1-picrylhydrazyl radical scavenging activity was determined by following the protocol of Barba-Pedrero et al. (2021) methodology was used to test. For this 100 µL of extract added to 3.9 mL of 0.1 mM DPPH solution, incubated in the dark for 30 minutes and absorbance measured at 517 nm by using spectrophotometer.

$$\% \text{ inhibition} = [(A_control - A_sample) / A_control] \times 100. \quad (2)$$

2.6.4. Ferric Reducing Antioxidant Power (FRAP)

Ferric Reducing Antioxidant Power was determined using the procedure outlined by Murungweni et al. (2024). After mixing 2.9 mL of FRAP reagent (acetate buffer: TPTZ: FeCl3=10:1:1) with 100 µL of extract, the mixture was incubated for 30 minutes at 37°C. 593 nm absorbance; µM TE/100 g.

2.7. FTIR Spectra Analysis

ATR-FTIR spectroscopy followed (Thanni et al., 2024). Samples analyzed on PerkinElmer Spectrum Two (Waltham, MA, USA), 4000–400 cm^{-1}, 64 scans, 4 cm^{-1} resolution. Spectra processed for baseline correction and normalization using OMNIC software, focusing on carbohydrate (1200–800 cm^{-1}) and protein (1700–1500 cm^{-1}) regions.

2.8. Statistical Analysis

All experiments were conducted in triplicates and the resulting data were analyzed by using analysis of variance (ANOVA) using Statistix 8.1 software. Means were separated by Tukey's Honestly Significant Difference (HSD) test, and differences were considered statistically significant when ($p \leq 0.05$).

3. Results and discussion

3.1. Malting characteristics

The germination rate increased steadily from 0% at day 0 to 98.00% in barley, 88.33% in corn, and 97.00% in rice at day 6. After six days of malting, the germination rate was observed to be considerably (*$p \leq 0.05$*) higher than un-malted one (Table 1). Malting yield increased to 77.00% in barley, 79.67% in maize, and 78.00% in rice at day 6 considerably (*$p \leq 0.05$*) higher after 6-day than 0-day (Table 1). Diastatic power increased consistently in all the cereals, from 26.67ºDP to 134.97ºDP in barley, 7.67ºDP to 37.66ºDP in corn, and 15.00ºDP to 95.01ºDP in rice, showing significant (*$p \leq 0.05$*) increase in diastatic power after 6-day malting compared to 0-day (Table 1). Similar trend was

observed in α-amylase activity showing increasing trend across cereals, from 0.51 CU/g to 139.94 CU/g in barley, 0.30 CU/g to 75.14 CU/g in corn, and 0.50 CU/g to 149.81CU/g in rice, showed a significantly ($p \leq 0.05$) higher alpha-amylase activity after 6-day as compared to 0-day (Table 1). All three cereals showed a steady decrease in phytic acid content, from 7.11 mg/g to 3.72 mg/g (48% reduction) in barley, 10.42 mg/g to 7.39 mg/g (29%) in corn, and 36.92 to 19.03 mg/g (48%) found in rice, showing relatively lower values of phytic acid after day 6 when compared to native (Table 1). This showed that malting can boost germination, diastatic power, and α-amylase activity by activating enzymes that mobilize starch. Barley has superior malting properties, with a germination rate of 98% and diastatic power at 134.97ºDP, compared to corn and rice.

Table 1. Effect of malting days on the malting properties of different cereals

Cereals	Days	Germination rate (%)	Malting yield (%)	Diastatic power (°DP)	α-amylase (CU/g)	Phytic acid (mg/g)
Barley	0	0	0	26.67±2.89^{k}	0.51±0.01^{m}	7.11±0.04^{g}
	6	98.00±0.82^{a}	77.00±0.82^{j}	134.97±4.85^{e}	139.94±2.80^{k}	3.72±0.21^{m}
Corn	0	0	0	7.67±2.52^{i}	0.30±0.02^{m}	10.42±0.18^{d}
	6	88.33±1.25^{e}	79.67±1.25^{i}	37.66±2.52^{h}	75.14±1.50^{j}	7.39±0.04^{i}
Rice	0	0	0	15.00±5.00^{ij}	0.50±0.02^{m}	36.92±1.05^{a}
	6	97.00±0.82^{b}	78.00±0.82^{j}	95.01±5.00^{c}	149.81±3.00^{b}	19.03±1.08^{f}

Similar improvements in germination rates have been observed in by Frančáková et al. (2012) reported improved germination in malted barley, where germination like germination rate may be correlated with enzymes activity and starch modification. Likewise, Guimarães et al. (2025) observed malt yields in malted rice, where rice malt as an adjunct lowered production costs by 2–12% with yields comparable to barley. Furthermore, Kong et al. (2024) highlighted how rice cultivar variations and malting parameters significantly influence overall yields and suitability for brewing. On the other hand, a reduction in antinutritional components, particularly phytate, has been consistently observed in malted finger millet and other cereals. Atuna et al. (2022) observed significant decreases at 24, 72, and 96 hours of malting, which appear to be associated with the improvement of nutritional profiles. The findings are reinforced by Bello and Udo (2018), who reported that conventional processing methods reduce the levels of phytate in grain flours, increasing both nutritional and functional qualities.

3.2. Proximate Composition

Moisture content decreased steadily in barley, corn, and rice from day 0 to day 6, with significantly lower levels ($p \leq 0.05$) after day 6 (see Table 2) might be due to killing process. Crude protein decreased steadily in all three cereals: 12.97 to 11.85% in barley, 10.16 to 9.73% in corn, and 7.56 to 5.64% in rice, with a significant ($p \leq 0.05$) decrease after 6 days compared to day 0 (Table 2). Crude fat content of the three cereals decreased steadily from 2.50 to 2.35% in barley, 0.71 to 0.63% in rice and 4.26 to 3.79% in corn. While ash and crude fiber content showed a significantly higher ash content after 6 days of malting as compared to 0 day across all the cereals. All three cereals showed a steady decline in crude fat content, from 2.50% to 2.35% (6%) in barley, 4.26% to 3.79% (11%) in corn, and 0.71% to 0.63% (11%) in rice; while ash content increased steadily from 2.39% to 2.62% (10%) in barley, 2.12% to 2.34% (10%) in corn, and 1.28% to 1.41% (10%) in rice; levels were substantially ($p \leq 0.05$) higher after day 6 than they were on day 0 (Table 2). Similarly, crude fiber increased

from 6.58% to 6.80% (3%) in barley, 3.20% to 3.47% (8%) in corn, and 1.55% to 1.82% (17%) in rice. Likewise, NFE increase consistently from 63.09% to 70.48% (12%) in barley, 67.95% to 75.25% (11%) in corn, and 76.57% to 85.48% (12%) in rice, showing significant ($p \leq 0.05$) after day 6 compared to native (Table 2).

Table 2. Impact of malting on the proximate analysis of cereal

Cereals	Days	Moisture content	Crude protein	Crude fat	Ash content	Crude fiber	NFE
Barley	0	12.47±0.29^{a}	12.97±0.25^{a}	2.50±0.03^{b}	2.39±0.07^{abcd}	6.58±0.61^{c}	63.09±0.43^{f}
	6	5.90±0.12^{b}	11.85±0.08^{d}	2.35±0.01^{b}	2.62±0.04^{a}	6.80±0.05^{c}	70.48±0.12^{a}
Corn	0	12.07±0.16^{a}	10.16±0.16^{e}	4.26±0.20^{c}	2.12±0.12^{e}	3.20±0.20^{b}	67.95±0.25^{e}
	6	5.45±0.11bcd	9.73±0.14^{f}	3.79±0.05^{c}	2.34±0.08^{bcde}	3.47±0.^{22b}	75.25±0.04^{bc}
Rice	0	12.32±0.31^{a}	7.56±0.08^{g}	0.71±0.18^{a}	1.28±0.05^{f}	1.55±0.05^{a}	76.57±0.84^{b}
	6	5.03±0.06^{ede}	5.64±0.05^{j}	0.63±0.07^{a}	1.41±0.01^{f}	1.82±0.08^{a}	85.48±0.15^{a}

From a nutritional aspect, the decrease in protein content (e.g., barley decreased from 12.97% to 11. 85%) might be due to proteolysis exceeding synthesis, as reported by Kumar et al. (2021) and Afify et al. 2012. In contrast to the findings of Singh et al. (2017) and Ukpong et al. (2022), who reported fat losses in sorghum and rice, our studies found reductions in crude fat across grains (6-11%) and moisture reductions (5.03-5.90%) due to kilning. Similar decreases have been observed in malted cereals, where fermentation and malt addition resulted in lower moisture (Forsido et al., 2020). Furthermore, determination of malting conditions showed malts with lower moisture than grains (Okonkwo et al., 2021). Ash and fiber increases (10% and 3–17%, respectively) reflect relative mineral concentration and cell wall restructuring, as seen in malted cereals where malting increased ash while decreasing lipid (Traoré et al., 2004). Furthermore, changes in physicochemical characteristics showed ash increase in germinated flours (Yang et al., 2021). Our results aligned with Kaur and Gill (2021), showing increase in fiber content after malting. NFE increases (11–12%) indicate amylase-driven carbohydrate simplification, consistent with malted cereals where malting increased total sugar due to amylase breaking down carbs (Atuna et al., 2022). Furthermore, grain fermentation and malting increased carbohydrate contents (Okonkwo et al., 2021).

3.3. Phytochemical Properties

TPC increased steadily across the cereals from 161.32 mg GAE/100g to 220.76 mg GAE/100g in barley, 140.44mg GAE/100g to 220.76mg GAE/100g in corn, and 121.97GAE/100g to 169.36mg GAE/100g in rice, with higher TPC values after 6-days of malting as compared to 0-day (Table 3). Similarly, TFC increase significantly across the cereals, from 49.99mg QE/100g to 104.02mg QE/100g in barley, 39.92mg QE/100g to 65.96mg QE/100g in corn, and 27.36mg QE/100g to 58.94mg QE/100g in rice after 6 days of malting (Table 3).

DPPH scavenging activity increased from 36.13% to 62.36% in barley, 46.86% to 70.13% in corn, and 27.90% to 57.57% in rice showing higher results after malting (Table 3). Likewise FRAP showed significant increase in anti-oxidant power after malting, which increased from 1235.10µM TE/100g to 1411.40µM TE/100g in barley, 619.75µM TE/100g to 752.92µM TE/100g in corn, and 344.94µM TE/100g to 513.11µM TE/100g in rice.

Table 3. Effect of malting on the phytochemical and Anti-oxidant properties of cereal

Cereals	Days	TPC (mg GAE/100g)	TFC (mg QE/100g)	DPPH (%)	FRAP (µM TE/100g)
Barley	0	161.32 ± 3.55^{gh}	49.99 ± 1.3^{ghi}	36.13 ± 0.90^{h}	1235.10 ± 9.59^{f}
	6	220.76 ± 4.43^{a}	104.02 ± 3.74^{a}	62.36 ± 1.03^{bc}	1411.40 ± 5.91^{a}
Corn	0	140.44 ± 3.45^{jk}	39.92 ± 1.38^{jk}	46.86 ± 3.17^{efg}	619.75 ± 5.19^{j}
	6	220.76 ± 0.57^{d}	65.96 ± 0.99^{d}	70.13 ± 1.72^{a}	752.92 ± 6.40^{g}
Rice	0	121.97 ± 2.60^{l}	27.36 ± 0.89^{m}	27.90 ± 1.16^{i}	344.94 ± 3.35^{p}
	6	169.36 ± 2.04^{efg}	58.94 ± 2.20^{ef}	57.57 ± 0.92^{d}	513.11 ± 6.57^{k}

This increase could be attributable to enzymatic release of bound phenolics, and synthesis of new phenolic compounds under germination stress, and cell wall modifications. Similar increases have been observed in malted grains, where malting induced additional polyphenols (Vingrys et al., 2022). These observations aligned with Udeh et al. (2018) in finger millet and Murungweni et al. (2024) in malting periods showing increasing trend after malting. DPPH and FRAP enhancements reflect elevated phenolics as electron donors, consistent with Niroula et al. (2019) in malted barley and Mahmoudi et al. (2015) in barley malt rootlet extracts. Koren et al. (2019) found similar increases in DPPH and FRAP were noted in various cereals. However, corn's potential for antioxidant applications is suggested by its maximal DPPH (70.13%) and barley's dominance. When applied to rice, Zhou et al. (2020) reported a connection between elevated flavonoid concentration and metabolic alterations during malting process.

3.4. FTIR Spectra Analysis

FTIR spectra exhibited consistent changes across all three cereals, with alterations in peak intensities and positions from day 0 to day 6, indicating modifications in functional groups such as carbohydrates (C–H stretching at 850–1164 cm^{-1} and C–O glucose ring at 1020–1156 cm^{-1} for rice; crystallinity ratio at 1047/1022 cm^{-1} for barley and corn) and proteins (Amide I at 1700–1600 cm^{-1} for barley), with significantly ($p\leq0.05$) different spectral profiles after malting compared to unmalted seeds (Figures 1–6). Structurally, FTIR showed enzymatic hydrolysis of starch with diminished molecular order and slight protein degradation/conformational changes. These modifications could be attributable to enzymatic activities during malting, including amylase-induced starch hydrolysis leading to unfolding of carbohydrate structures and reduced crystallinity, as well as protease-driven protein depolymerization resulting in decreased ordered secondary structures like α-helix and β-sheets. Similar spectral changes have been observed in malted rice, where increased germination time (3–7 days) and kilning temperature (40–60 °C) caused fluctuations in band intensities at 850–1164 cm^{-1} (C–H stretching) and 1020–1156 cm^{-1} (C–O stretching), reflecting carbohydrate unfolding due to α- and β-amylase hydrolysis of starch (Lekjing & Venkatachalam, 2020). Furthermore, in germinated barley, ATR-FTIR showed decreasing proportions of protein secondary structures (α-helix at ~1650 cm^{-1}, β-sheets at 1612–1640 cm^{-1}) and reduced starch crystallinity (1047/1022 cm^{-1} ratio) over 0–72 hours, attributed to protease and amylase depolymerization for seedling growth (Kaur & Gill, 2021). For corn, IR analysis during germination (up to 9 days) confirmed enzymatic fractionation of amylose and amylopectin, with a lower 1047/1022 cm^{-1} ratio (from 1.042 to 0.838), explained by amylases selectively degrading amorphous starch regions for energy

without altering crystalline structure (Wang et al., 2023).

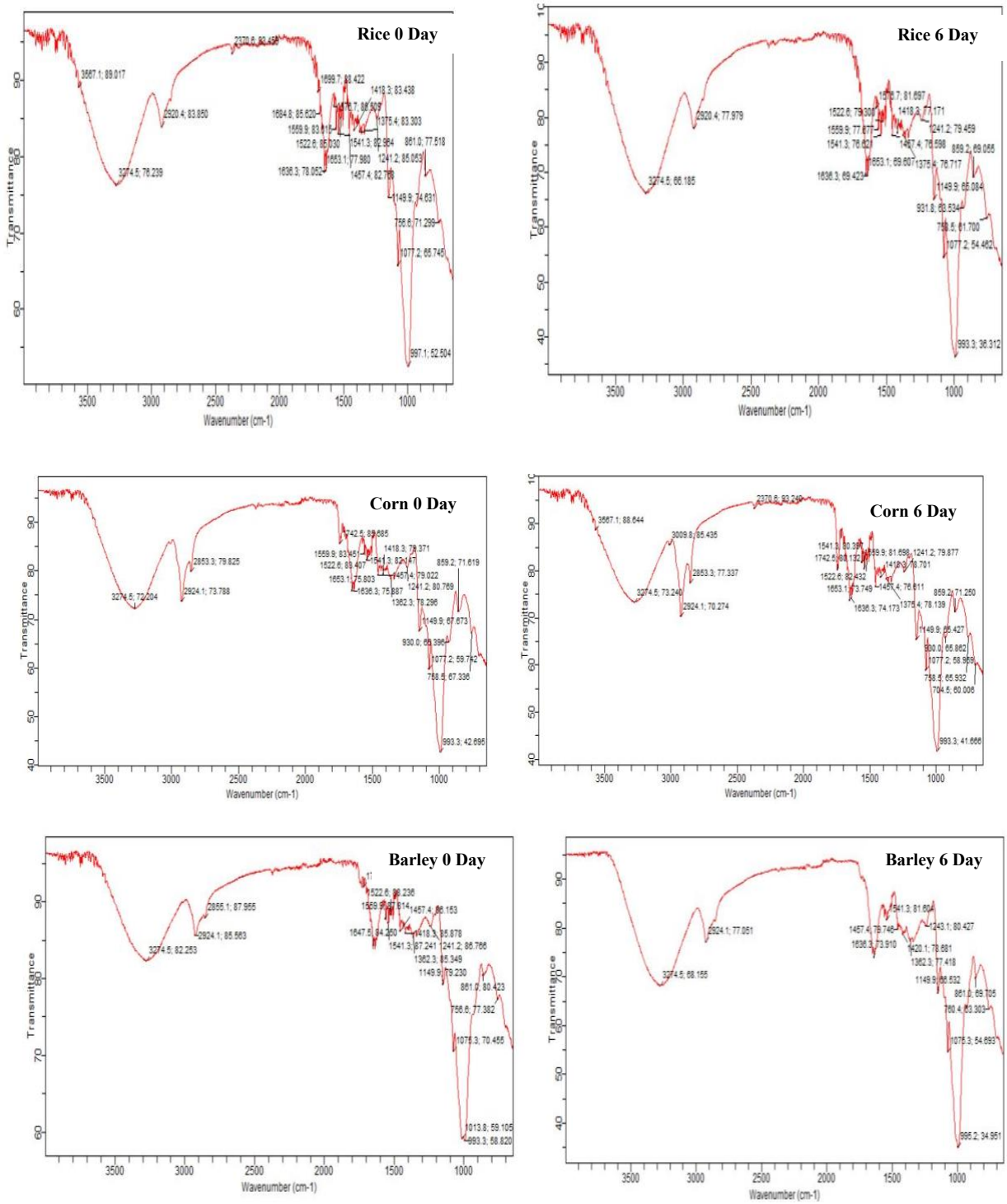

Figure 1. Comparison of FTIR Spectra at 0 day and 6 days of malting

3.5. X-ray diffraction XRD

X-ray diffraction (XRD) measurements revealed characteristic A-type crystallinity in all unmalted cereals, with diffraction patterns showing strong reflections at approximately 15° 2θ (d-spacing ~5.9 Å), a doublet at 17–18° 2θ (~5.2–4.9 Å), and another at 23° 2θ (3.9 Å), reflecting the compact monoclinic packing of amylopectin helices in cereal starches, where initial intensities peaked around 150–160 counts

in the 15–25° 2θ interval and decayed to baseline beyond 50° 2θ, indicating semi-crystalline structures with baseline crystallinity indices (CI) estimated at 30–45% as shown in fig 2.

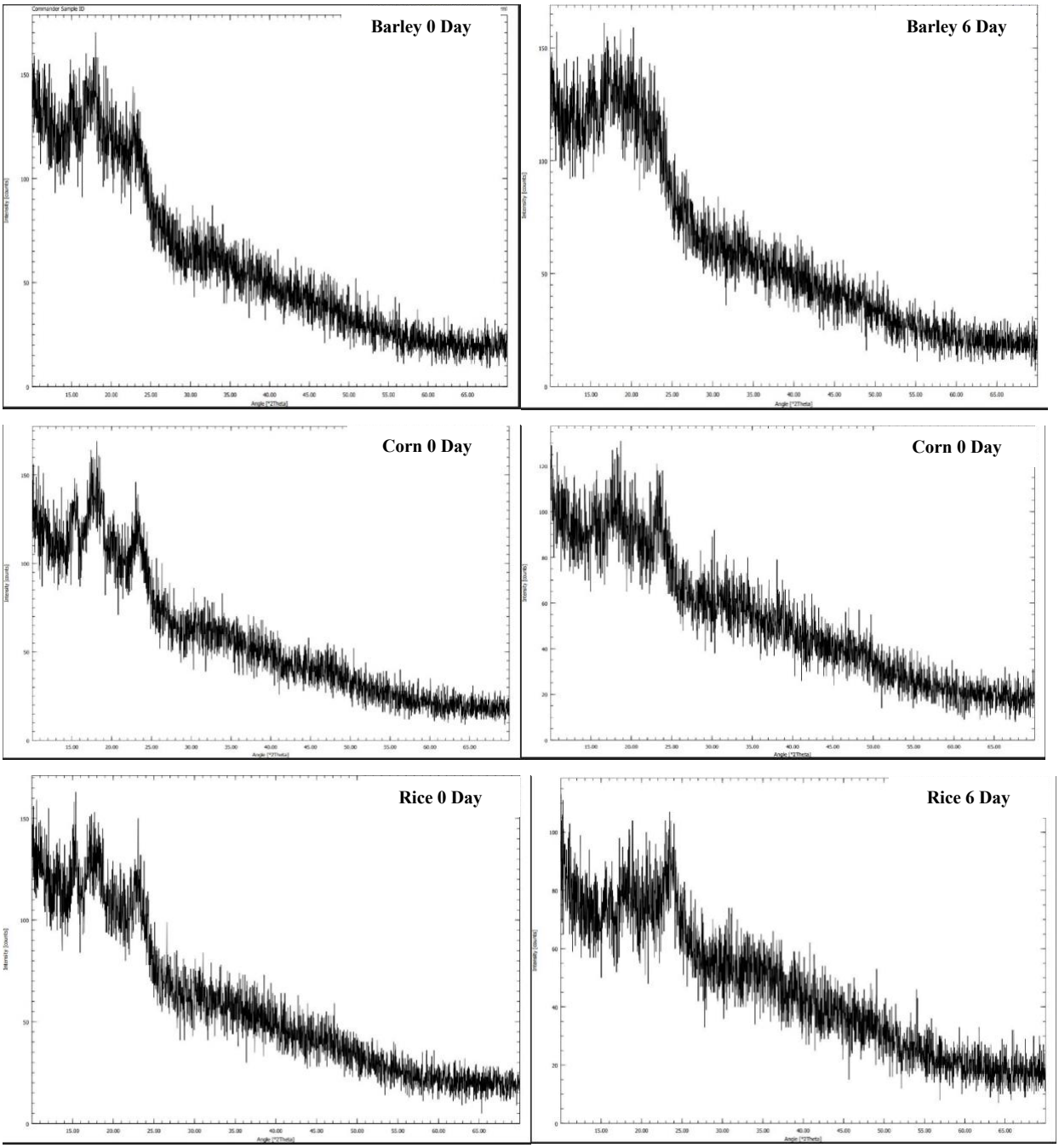

Figure 2. Comparison of XRD pattern at 0 day and 6 days of malting

The malting process induced a time-dependent reduction in peak intensity and broadening, most evident after malting process, signifying progressive erosion of crystalline domains without polymorphic transitions, such as the absence of B- or V-type patterns; although explicit CI values were not reported, visual analysis suggested a 10–25% crystallinity drop by day 5, accompanied by an increase in full width at half maximum (FWHM) from 0.3–0.5° to 0.5–0.7°, denoting smaller crystallite sizes and defect introduction per Scherrer's equation,

changes attributed to α-amylase activity (109.89–134.78 CU/g) and other hydrolases preferentially degrading amorphous regions before crystalline ones, thereby liberating soluble dextrin and sugars. Cereal-specific trends showed barley with the most resilient structure, featuring pronounced persistent peaks (initial CI ~35–40%) due to its high amylose content (~20–25%) forming stabilizing complexes that delay enzymatic penetration, resulting in a ~15–20% intensity drop by day 5 correlated with elevated α-amylase and diastatic power (80.00–120.02° DP); corn exhibited intermediate alterations with ~20% intensity reduction and broader peaks, reflecting larger granules (10–20 μm) and moderate amylose (18–24%); while rice displayed the steepest decline (~25% by day 5) with smoother diffractograms, owing to smaller granules (3–8 μm), higher amylopectin, and enhanced moisture absorption during steeping with 0.5% NaOH, accelerating amorphization. This gradient (barley > corn > rice) arises from differential enzyme activation, where gibberellins trigger aleurone-layer amylase secretion, eroding amorphous branches first then crystalline helices, with kilning (55–65°C) potentially inducing partial retrogradation but mainly stabilizing the amorphous state. South Korean barley cultivars maintained A-type patterns but reduced CI by ~1–5%, linked to enzymatic selectivity in amorphous zones (Liu et al., 2024); Park et al. (2024) on Korean black barley and rice adjuncts reported a CI order of high-amylose rice > standard rice > malt, with no polymorphic shifts but reduced CI post-malting due to amorphous hydrolysis; Yu et al. (2018) validated rice rapid changes, showing adjuncts decrease overall starch crystallinity by increasing soluble fractions and enhancing fermentation efficiency and Lekjing and Venkatachalam (2020) noted similar trends in rice, where extended malting (3–7 days) lowered CI and correlated with higher antioxidant extraction. Overall, these XRD profiles affirm malting's role in structural depolymerization, enhancing digestibility, bioactive release, and applicability in functional foods and brewing without major polymorphic shifts but with significant amorphization supporting enzymatic hydrolysis narratives.

4.Conclusion

The 6-days malting process significantly increased the nutritional characteristics, malting properties and antioxidant activity of barley, corn, and rice, and proved to be an effective natural bio-processing approach in improving the quality of cereal. Key improvements were near complete germination, increased enzymatic activity (diastatic power and alpha-amylase), decreased anti-nutritional phytic acid and changes in proximate composition towards an increased available carbohydrate and mineral content. Phytochemical enhancement which includes: increased phenolics, flavonoids and antioxidant capacities (DPPH and FRAP) indicate the role of malting in increasing bioactive compounds that may have health enhancing property such as lower oxidative stress and increased bioavailability. Barley was most sensitive as would be expected from a traditional malting application and corn and rice provided gluten-free options and large reductions in anti-nutrients. FTIR analyses were also key to confirm molecular restructuring that supports the implication of enzymatic depolymerization processes of starches and proteins. Overall, these findings confirm the use of malting as a cost-effective approach to optimize cereals for functional food, infant nutrition and brewing to effectively contribute to food security and promotion of health.

5.References

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