Bernardo P. Guimaraes, Heena Rani and Scott Lafontaine

Identifying and overcoming challenges in scaling up malted rice for commercial malting and brewing

Barley has long been the primary grain used for malting and brewing, but projected declines in barley yield, growing demand for gluten-free products, and interest in novel flavours are creating a market for alternative malts. Rice, a high-yielding, gluten-free crop with stable production forecasts, shows strong potential but remains underexplored at an industrial scale. This study evaluated the scale-up of malting for four rice varieties from laboratory batches (~0.5 kg) to pilot-scale production (~150 kg), with trials conducted across two malthouses and six breweries. Compared with barley, rice kernels exhibited distinct morphological and physiological characteristics, including a slenderer grain shape, lower germination energy, and reduced water uptake capacity. These traits created handling challenges during steeping and transport, requiring equipment modifications. Despite these hurdles, pilot-scale malting produced viable malt with extract yields of 38–64% and free amino nitrogen levels comparable to barley. Enzymatic activity profiles revealed lower α- and β-amylase activity, but significantly higher glucoamylase and limit dextrinase activity. Brewing trials demonstrated the potential of malted rice as an adjunct capable of contributing novel flavour and colour attributes. However, adequate malt modification or the use of exogenous enzymes was essential to prevent stuck mashes caused by starch gelatinization. Sensory evaluation highlighted cereal-like and nutty notes in non-pigmented malted rice, sake-like notes in aromatic varieties, and smoky characteristics in the pigmented variety, which also produced a purple-coloured wort. Overall, this work provides the first industrial-scale assessment of malted rice, demonstrating its technical feasibility and its distinct enzymatic and sensory contributions to brewing. Although process adjustments are required, malted rice offers a promising pathway to diversify brewing raw materials, expand gluten-free beer production, and reduce reliance on barley under a changing climate.

Descriptors: rice, rice malt, rice beer, commercial-scale trials, scale-up.

1 Introduction

Historically, due to German purity law, malted barley, hops, and water (and later, yeast) have been regarded as the main raw materials for beer production [1, 2]. In general, barley is adapted to cooler climates, and global barley yield is projected to decrease by 9% to 16% [3-5]. These estimates do not account for losses in quality associated with heat stress and increased protein content [6]. Alternative malting grains that are more heat tolerant and potentially more sustainable could therefore provide a viable long-term solution for the brewing industry.

Alternative malts can be produced from a variety of grains, including rice, maize, kernza (*Thinopyrum intermedium* subsp. *intermedium*), and sorghum. From an agronomic perspective, maize has the highest yield, reaching three to four times that of barley, and is already produced at industrial scale. However, maize is less suitable for malting because of its oil-rich germ and flavour attributes (e.g., dimethyl sulfide, DMS) as well as high gelatinization temperature [7]. Therefore, maize use is generally limited to flakes, grits, syrup, and other degermed formats [8]. Kernza is a perennial grain that has also been studied for its malting potential [9]. However, field yield and total production remain extremely low compared with other grains (Table 1), and its small size and morphology make integration into commercial malting systems difficult [10].

Rice is a gluten free and tropical crop [11] that yields two to three times more than barley (Table 1). Compared with barley, rice also has a more stable projected yield (between -5% and +3%) [5]. When considering sustainability, global-warming potential (GWP) is an important metric used to normalise greenhouse gas emissions and is expressed as tons of CO_2-equivalent per ton of grain. In general, rice has roughly twice the GWP of barley; however, this value is highly dependent on agricultural practices [10], as reflected by the wide GWP range reported for rice compared with other crops.

Rice is the third most cultivated crop worldwide, with a production of 745 million metric tons annually [12, 13], and the United States ranks as the 13th largest rice producer and the 6th rice exporter in the world with 9.9 million and 3.2 million metric tons, respectively

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Table 1 Mean agronomic data, price, and sustainability data for various malting grains [10]

Grain type	Region	Type	Yield [t/ha]	Harvested area [1000 ha]	Production [1000 t]	Price [2024 $/t]	GWP [tCO_2e/t grain]
Long grain rice	Arkansas	Hybrid	12.06	264	2,230	NA	NA
		Pureline	10.90	192	1,582	NA	NA
Maize	USA	All	11.13	33,676	363,449	271 ± 40	0.05-1.18
Rice	USA	Short, medium, and long grain	9.48	1,078	9,122	441 ± 42	0.23-5.55
Barley	USA	Feed and malting barley	3.92	978	3,827	353 ± 37	0.26-0.57
Wheat	USA	All	3.28	16,326	51,981	338 ± 54	0.06-1.57
Sorghum	USA	All	3.26	2,356	9,921	270 ± 40	0.08-012
Kernza	USA	All	1.68	1.619	0.3	7,165	NA
Millet	USA	All	1.64	198	320	305 ± 150	1.51
Fonio	Western Africa	All	0.75	860	645	45.90	NA

Global-warming potential (GWP) ranges were obtained from the literature. Agronomic values (yield, harvested area, and production) are averages calculated from data collected between 2013 and 2023. Price is the average weekly price for 2022 and 2023, adjusted for inflation. NA indicates that data were not available or were not applicable. Data from Guimaraes, et al. [10].

[12, 14]. US rice is concentrated in Arkansas (49%), California (18%), Louisiana (14%), Missouri (8%), Texas (6%), and Mississippi (5%) [15]. The majority of rice produced in the United States is long-grain (defined by a length-to-width ratio > 3.4), whereas medium-grain (2.2 < L/W < 3.3) and short-grain (L/W < 2.2) varieties are cultivated for specific end-uses, including sushi and specialized rice products [16]. Rice is mostly used for human consumption as milled rice (also known as white rice) [16]. To produce edible white rice, paddy rice (also known as rough rice) is dehulled to remove the husk, then milled to remove the bran layers and germ through friction [16]. The friction may break the rice kernel, generating what is called broken rice. Edible white rice (head rice, > 75% intact grain length) has a higher economic value than brokens (< 75% intact grain length) as consumers see brokens as a defect when consuming rice [16-18]. Therefore, broken rice is commonly used as raw material in brewing and the pet food industry or is further processed to generate other rice products (e.g., rice flour and rice syrup) [19]. Broken rice is typically classified as second heads (50–75% intact grain length) or brewer's rice (< 25%) [18].

In brewing, rice is commonly used as an adjunct (i.e., a starch source that supplements malted barley), primarily because of its high starch content, extract efficiency, and lower cost [17, 20]. Rice can also impart favourable sensory properties, such as a neutral flavour, light body, and greater drinkability, owing to its lower lipid and protein contents [11]. Lower lipid and protein contents can potentially contribute to improved wort and beer flavour stability by reducing oxidative staling precursors and aldehydes, thereby extending shelf life compared with beers made from 100% barley [21].

However, the use of rice as an adjunct is not without technological challenges, as rice is generally regarded as a high-gelatinisation-temperature crop (~70–85 °C) compared with barley (56–68 °C). Gelatinisation temperature (GT) is the temperature at which starch loses its crystallinity and becomes much more susceptible to enzymatic hydrolysis (saccharification) refers to the breakdown of starch into fermentable sugars [2, 22, 23]. Because rice GT is above the optimal temperature range for barley amylolytic enzymes, brewing with rice typically requires two vessels: one for rice starch gelatinisation (a cereal cooker) and another to saccharify the gelatinised starch (the mash tun), where the bulk of the malted barley is added. This approach is referred to as the American double-mash [20] and is mostly used by large-scale breweries like Anheuser-Busch [24]. In contrast, craft breweries commonly operate single-vessel systems and therefore tend to prefer pre-gelatinised rice forms (e.g., flaked rice, extruded rice, rice syrup), which can be added directly to the mash tun with malted barley for saccharification [8]. In addition, rice varieties at the lower end of the GT range may overlap with barley (59–75 °C) [20, 22] and could therefore be used by craft brewers in single-vessel systems.

Current research on rice in brewing includes investigating factors that drive extract yield in milled rice [20]; the nutritional and sensory impacts of using pigmented rice as adjuncts [25, 26], and the use of malted rice as both base and speciality malts [27-36]. Interest in malted rice is growing, and this may be driven by the growing gluten-free market, with an annual growth rate of ~12.5% [37], its unique sensorial attributes, and demand for locally sourced raw materials. Malted rice is produced in a similar fashion to malted barley (i.e. steeping, germination, and kilning) but at higher steeping and germination temperatures, lower kilning temperature, and longer kilning time [11, 35, 38]. Research on malted rice has demonstrated promise in terms of malting [11, 28, 32, 33], brewing [27, 28, 39], sensorial quality [28, 39], and economic competitiveness [10]. Reported rice malting qualities include extract values between 50% and 73% [32, 39]; free amino nitrogen (FAN) levels comparable to those of malted barley [32]; and good self-saccharification capacity [32, 33, 35]. Sensory attributes include opportunities for novel colours, as malted pigmented rice can produce a red-purple wort, as well as distinctive flavour profiles [27, 32, 33].

Mayer, et al. [39] produced 100% malted rice beer with moderate fermentability (71.5-73.0%), which is lower than that of beer made from 100% malted barley (78–85%) [40]. However, this lower fermentability could be advantageous for producing low-alcohol beers (LAB, <2.5% ABV) and no-alcohol beers (NAB; legally designated “non-alcoholic brews”, “near beer”, “malt beverage”, or “cereal beverage” in the U.S.) with greater body [41]. Sensory studies suggest that malted rice can function either as a base malt, imparting barley-like cereal and nutty notes, or as a speciality malt, contributing buttery/vanilla aromas in aromatic rice varieties or fruity/medicinal notes in malted purple-pigmented rice varieties [42]. Finally, malted rice has been reported to require approximately half the land area required by barley to generate an equivalent amount of extract, offering improved land-use efficiency and lower brewing costs relative to milled rice, while remaining ~12% more expensive than malted barley [10]. Water demand must also be considered, as rice, particularly when cultivated in flooded paddy fields, can require two to three times more water than barley [43, 44]. However, alternative water management systems (e.g. alternate wetting and drying irrigation) may reduce both rice water demand and GWP [45].

Identifying locally sourced alternative grains with industrial malting potential is vital for sustaining brewing capacity and promoting local agriculture. Although malted rice has been commercially available and studied for more than a decade, existing work has been limited to micro-malting (~1 kg/batch) or benchtop-scale malting (~8 kg/batch) systems and laboratory-scale brewing and analyses. There is no public information on the upscaling of malted rice production or on the challenges faced by commercial malthouses and breweries when adopting malted rice at industrial scale. The aim of the present study was therefore to identify key pain points, propose practical solutions, potential applications, and evaluate the feasibility of producing and brewing with malted rice at industrial scale.

2 Materials and methods

2.1 Experimental workflow

To assess the major challenges associated with malted rice from malting through brewing at the industrial scale, four rice varieties were selected for malting in commercial malthouses and subsequent evaluation by commercial breweries (Fig. 1). The varieties were chosen based on their performance in previous research trials. A total of 500 kg of rough rice from each variety were sent to commercial malthouses equipped with pilot-scale malting systems. Malting trials were conducted using two different systems; cylindroconical vessels and immersion box vessels, to accommodate the specific requirements of rice malting. The resulting malts were subsequently sent to commercial breweries operating pilot brewing systems ranging from 0.6 to 10 hL. Qualitative feedback was then collected from brewers to identify the key challenges and limitations associated with using this alternative malt at the industrial scale.

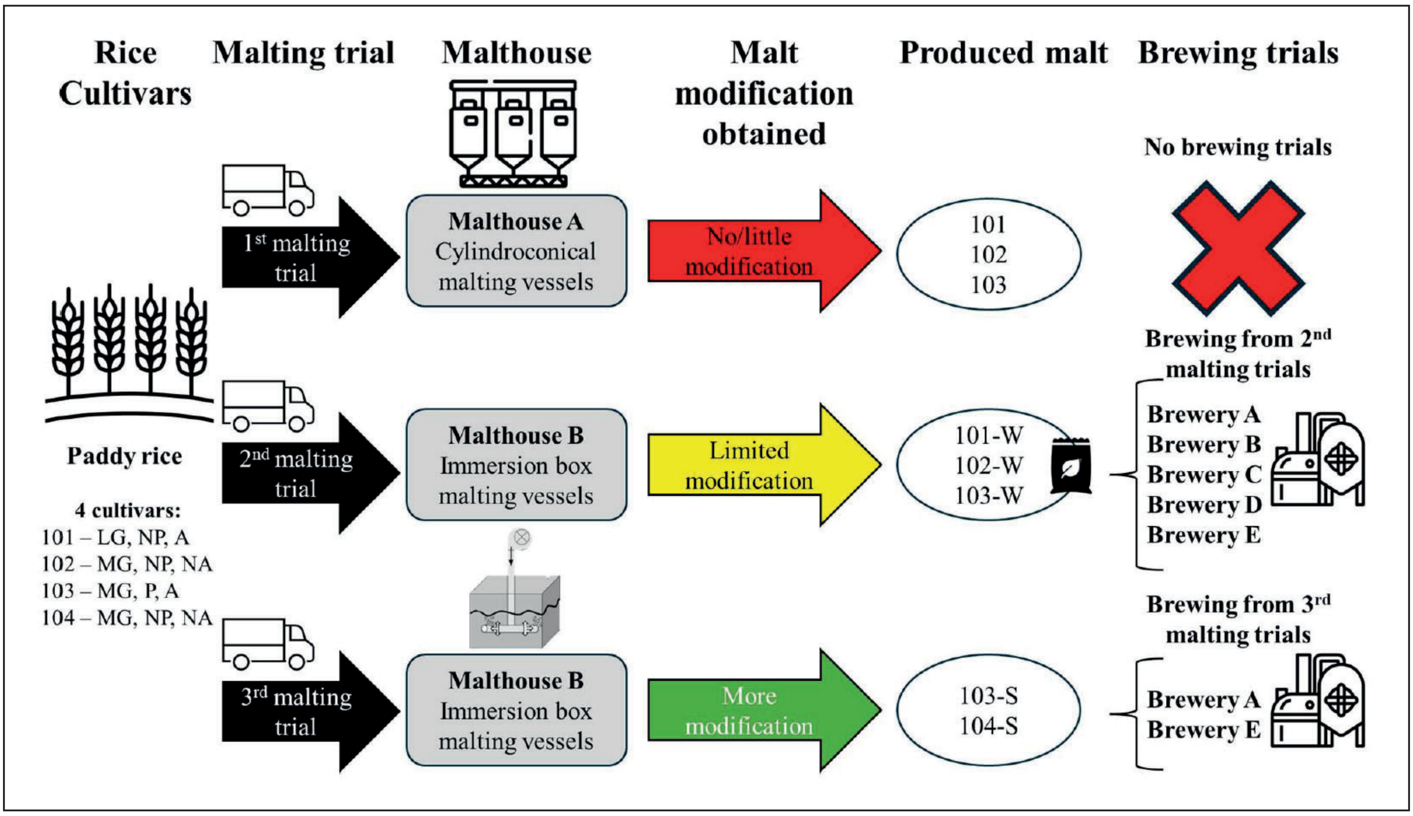

Fig. 1 Experimental workflow showing the characteristics of the rice cultivars, malting trials, partner commercial malthouses, degree of malt modification, malt produced in each trial, and brewing trials conducted by partner commercial breweries. Rice cultivars were classified as long-grain (LG) or medium-grain (MG), pigmented (P) or non-pigmented (NP), and aromatic (A) or non-aromatic (NA)

2.2 Raw materials

The four best-performing rice varieties (101, 102, 103, and 104) were selected from previous screening of 20 rice samples [32] and subsequent sensorial evaluation of 10 out of the 20 samples [42]. The selected varieties were upscaled from laboratory scale (0.5 kg/batch) to pilot-scale production (150 kg/batch) (Figure 1). Two additional rice varieties, paddy rice A and B (PR-A and PR-B, respectively), were included to better understand process-related difficulties, but they were not upscaled.

Paddy rice was analysed for kernel size, germination energy, and starch properties (apparent amylose and gelatinisation temperature) using previously established methods [32]. Rice flour was boiled, reacted with triiodide, and the absorbance of the resulting solution was read at 620 nm using a UV-Vis spectrophotometer (Pharmaspec UV-1700, Shimadzu, Kyoto). Values were calculated using a calibration curve spanning from 0% to 30% amylose in amylopectin. Gelatinisation temperatures (onset, peak, and end) were determined by differential scanning calorimetry (DSC; model 4000, PerkinElmer, Boston, MA, USA) following the protocol of Patindol, et al. [48]. Kernel length and width were measured with a Vibe QM3 grain analyser (Vibe Imaging Analytics, Inc., Santa Cruz, CA, USA). Germination energy was determined as described by Mayer, et al. [35], using a procedure similar to ASBC Barley-3 [46] but conducted at 27 °C. Apparent amylose was quantified using the method described by Juliano [47].

2.3 Malting qualities

To better understand differences in water uptake between malting barley and paddy rice, a water uptake curve was generated following the methodology of Mayolle, et al. [49]. Five grams of paddy rice were weighed on an analytical balance and placed in a stainless-steel tea bag, with a total of 20 samples prepared. The paddy rice was soaked in excess room-temperature water (4 L at 21–23 °C) for 24 h. Beginning at 6 h of steeping, two replicates were removed at 2 h intervals, dried with paper towel to remove surface water, and weighed on an analytical balance. Water uptake was calculated as shown in Eq. 1. Paddy rice moisture content was determined according to ASBC Cereals-3 [46]. Two additional sets of steeping trials were performed to identify the best water profile: one evaluated the influence of water hardness (dissolved Ca^{2+} and Mg^{2+}) and pH (Supp. Table 1), and the other evaluated the effects of water hardness and aeration on rice water uptake (Supp. Table 2). In these trials, 1 kg of paddy rice was steeped in 15 L of soft or hard water for 72 h, followed by 24 h of natural air drying. Soft water was reverse-osmosis water with 120 ppm total dissolved solids (TDS), and hard water was city water at 606 ppm TDS.

Moisture Content

$$\text{in−process} = 1 - \left(\frac{\text{mass}_{\text{dry sample}} * (1 - \text{Moisture Content}_{\text{dry sample}})}{\text{mass}_{\text{wet sample}}}\right) \text{(Eq. 1)}$$

The paddy rice was then shipped to Malthouse A (cylindroconical vessels) for the first malting trial and to Malthouse B (immersion box vessel) for the second and third malting trials, which occurred during winter (W) and summer (S), respectively. The baseline malting procedure used was the same as that reported by Guimaraes, et al. [32], although the maltsters could adapt the protocol as they saw fit to account for variability in upscaling equipment and environmental conditions. Some benchtop-scale malting trials were also performed by Malthouse A to optimise the process for their equipment by varying steeping and/or germination time and temperature, as well as the use of gibberellic acid (GA), following the procedures shown in Supp. Table 3. Malting losses (i.e. the amount of dry matter lost during malting) were calculated according to Mauch, et al. [50].

Finally, the malted rice was evaluated for moisture, extract, and diastatic power using ASBC Malt 3, 4, and 6, respectively. The modified Congress mash followed the methodology of Mayer, et al. [35]. Extract, fermentability, pH, colour, protein, FAN, viscosity, and β-glucan were measured from the modified Congress wort using ASBC Wort-4, 5, 8, 9, 10, 12, 13, and 18, respectively. The activities of α-amylase, β-amylase, glucoamylase, and limit dextrinase were measured using Megazyme kits as previously described [32]. Malting losses on a dry basis (ML, % d.b.) were calculated using Eq. 2.

$$ML\ (\%d.b.) = \frac{m_{rice} * (1 - MC_{rice}) - (m_{malt} * (1 - MC_{malt}))}{m_{rice} * (1 - MC_{rice})} \text{(Eq. 2)}$$

To evaluate the impact of exogenous enzymes on alternative malts, thermostable α-amylase and pullulanase (Ceremix Flex, Novonesis, Bagsværd, Denmark) were added at different concentrations (0, 625, 1250, 2500, and 5000 ppm) at the start of a Congress mash containing malted rice 104. The resulting wort was then force fermented and analysed according to ASBC Malt-7.

2.4 Malting upscale

Pilot-scale malting at each malthouse was conducted by the respective local maltster, who had previously been informed of the steeping, germination, and kilning times and temperatures that were successful in the benchtop malting trials [32]. The maltsters were allowed to adjust these parameters, as well as the oxygenation rate, to accommodate differences in equipment design and facility-specific operating conditions. Detailed malting logs and batch numbers are provided in Supp. Table 4.

2.5 Brewing qualities

To compare the way brewers typically use rice as an adjunct with the performance of malted rice, paddy rice 102 and 103 were milled and polished according to Aitkens, et al. [20] using a Zaccaria mill (PAZ/1-DAT, Zaccaria USA, Anna, TX, USA). The surface lipid content (SLC) of the milled rice was then determined using a DA 7250 At-line near-infrared (NIR) instrument (PerkinElmer, US LLC, Shelton, CT, USA). If SLC exceeded 0.50%, the milled rice was polished again until SLC was <0.50%. Milled and malted rice were then sent for analysis as adjuncts and tested at inclusion ratios of 40% and 60% to evaluate performance in high-gravity and high-adjunct brewing (Supp. Table 5).

The fine and coarse extract of the malted rice were determined using the optimised modified Congress mash described by Mayer, et al. [35]. Fine grinding was performed using a cyclone mill (UDY Cyclone Mill, UDY Corp., Fort Collins, CO, USA), and coarse grinding was performed using a grain mill (SS Grain Mill, SS Brewtech, Wildomar, CA, USA) with a milling gap of 0.95 mm. The real degree of attenuation (RDF) was determined using ASBC Beer-6 [46]. Particle size distribution after fine and coarse milling at different mill gaps was also evaluated. The mill gaps tested were +2 (1.55 mm), 0 (1.25 mm), -2 (0.95 mm), and -5 (0.50 mm). One hundred grams of milled malted rice were shaken for 3 min using an autoshaker (RX-29, W.S. Tyler, Mesto, OH, USA) with U.S. Standard Testing Sieve Nos. 8 (2.380 mm), 12 (1.680 mm), 18 (1.000 mm), 20 (0.841 mm), and 60 (0.250 mm), with a bottom pan used to collect particles <0.250 mm. Material retained on each sieve was then weighed on an analytical balance (Supp. Table 6).

Malted rice from the second and third malting trials was distributed to breweries A, B, C, D, and E, each selected to align with the breweries' specific goals (base malts, coloured malts, or aromatic malts). To mimic commercial practice, brewers had complete autonomy in how they used the malted rice, including beer style, all-malt or adjunct brewing, mashing regime, use of brewing aids (e.g. yeast nutrient or exogenous enzymes), yeast choice, and fermentation parameters. Partner breweries were informed of the overall characteristics of the malted rice (sensory attributes, extract, and moisture), previous brewing trials, and a suggested mashing regime based on Guimaraes and Lafontaine [42] in case opted for all-malt trials.

2.6 Feedback from maltsters and brewers

A survey was designed using Qualtrics online survey software (Seattle, WA, USA) and sent to the breweries that participated in malting rice or brewing with malted rice for this study (Supp. Table 7). This study was approved by the Institutional Review Board at the University of Arkansas on March 31, 2025 (IRB #2503597950). All respondents gave consent to participate in the survey and could withdraw at any time without penalty. The primary objective of the survey was to identify operational challenges and practical limitations encountered when handling and processing malted rice as a novel brewing raw material and to guide further research trials.

3 Results and discussion

3.1 Rice characteristics used for commercial malting trials

Four Paddy rice samples were sent to Malthouse A for upscaling trials, along with two additional paddy rice (PR) varieties (PR-A and PR-B). The physical and physicochemical attributes of the paddy rice varieties are summarised in Table 2. In general, rice kernels were more slender than barley kernels, and only paddy rice 101 did not differ significantly from barley in length ($p<0.05$) (Table 2; Supp. Fig. 1). As with barley, sufficiently hydrated rice grains chitted and produced a shoot (Supp. Fig. 2). However, rice germination energy on day 5 (84.5–90.4%) was lower than what is typically expected with malting barley (>95%) [51].

Grain hydration dynamics dictate the duration of wet and dry rests during steeping. A logarithmic regression of in-grain moisture (Supp. Fig. 3) showed that, even after 24 h, the maximum moisture content for all varieties was only ~30%, which was significantly lower ($p<0.05$) than values reported for barley (>40%) [1, 51, 52]. Multiple grain and steeping characteristics, including husk presence, husk porosity, temperature, pH, and time, can affect moisture diffusion kinetics [52] and, consequently, germination [49]. To improve in-grain moisture in rice, one cultivar (PR-B) was steeped under different pH and hardness conditions (Supp. Table 1), whereas PR-A was steeped with and without aeration in soft and hard water (Supp. Table 2). No significant differences ($\alpha=0.05$) were observed among treatments (pH, hardness, or oxygenation), but significant

Table 2 Paddy rice (PR) characteristics and malted barley (P2R) for comparison

Sample	Type$^{\$}$	Characteristics	Dimensions$^{\$}$			Germination Energy		Gelatinization temperature		
			Length [mm]	Width [mm]	L/W	3rd day [%]	5th day [%]	Onset [°C]	Peak [°C]	End [°C]
P2R	Malted barley	Pale two-row	8.500^{b}	3.621^{a}	2.362	$>95\%^{a\#}$	$>95\%^{a\#}$	61.00	67.11	74.64
101	Long-grain rice	Aromatic, non-pigmented	8.675^{b}	2.512^{c}	3.514	84.5^{ab}	90.4^{abc}	66.28	72.26	79.24
102	Medium-grain rice	Non-aromatic, non-pigmented	7.411^{d}	2.957^{b}	2.561	90.4^{ab}	93.1^{ab}	67.40	73.27	80.08
103	Medium-grain rice	Aromatic, pigmented (purple bran)	7.740^{c}	2.785^{d}	2.796	86.7^{ab}	93.4^{ab}	74.16	78.00	83.14
104	Medium-grain rice	Non-aromatic, non-pigmented	7.401^{d}	2.967^{b}	2.511	88.1^{ab}	94.1^{ab}	64.26	71.86	79.55
PR-A*	Long-grain rice	Non-aromatic, non-pigmented	8.999^{a}	2.673^{e}	3.384	70.1^{b}	79.5^{bc}	NA	NA	NA
PR-B*	Long-grain rice	Hybrid, non-aromatic, non-pigmented	8.847^{a}	2.479^{c}	3.597	76.0^{ab}	78.0^{c}	NA	NA	NA

** – malted rice not upscaled. $^{\$}$Length and width were measured only on paddy rice. $^{\#}$Expected germination energy according to the literature [54]. Rice varieties are pure lines except for PR-B, which is a hybrid. NA indicates not analysed. Onset, peak, and end denote gelatinisation temperatures, which were obtained from a single measurement. Mean values are based on two replicates for length, width, and germination energy. Values not sharing a superscript letter are statistically different at $\alpha=0.05$ according to Tukey's test.*

Table 3 **Characteristics of malted rice from different malting trials in Malthouse A**

Treatment	Variety	α-amylase	β-amylase	Colour	Turbidity	DP	Extract	FAN	Moisture	pH	Kolbach Index	Total Protein	Viscosity	Steep-out moisture
		[DU]		[SRM]	[NTU]	[ASBC]	[%]	[ppm]	[%]		[%]	[%]		[%]
	P2R	24-53	555-849			161-198	79.8-79.9	175-244			32.5-43.9	8.4-10.6	1.48-1.53	45-50
Cold, short steep; 5-day germ	101	36.2	26	0.74	90.6	36	64.6	17	8.32	6.10	2.7	0.27	9.96	31.1
Warm long steep (80 h spray steep)	102	39.1	7	0.88	77.3	39	64.2	43	7.15	6.16	6.8	0.53	7.84	33.6
No change	PR-A	35.3	9	0.88	45.1	35	64.1	22	7.14	6.30	6.4	0.59	9.21	35.8
9-day germ, GA	PR-B	36.9	0	0.88	85.8	37	26.0	65	6.76	6.16	9.5	0.93	9.75	33.9
Extra-long immersions (56/84 h), 6-day germ, double GA	101	36.2	21	0.72	58.6	36	68.6	38	7.31	6.32	5.4	0.57	10.50	34.1

Colour was measured in standard reference method (SRM) units; turbidity in nephelometric turbidity units (NTU); and diastatic power (DP) in ASBC units. Kolbach index represents the ratio of soluble protein to total protein. Steep-out moisture is the moisture content at the end of steeping. GA denotes gibberellic acid. Barley ranges were taken from Rettberg [51] and Turner, et al. [55] Specific malting conditions for each trial are provided in Supp. Table 3.

differences were observed among varieties. Even so, values remained lower than those reported for barley (>40%) [1, 52, 53]. The highest value obtained (39.68%) was achieved using aeration and soft water; therefore, for the actual pilot-scale batches (180 kg), samples were steeped in aerated water.

3.2 First commercial malting trial – cylindroconical malting vessels

The first pilot-scale trials were conducted in cylindroconical malting vessels at Malthouse A. A pulley conveyor belt was used to move grain from storage into the steeping vessel; however, issues arose during grain handling. Paddy rice 101 moved without issues and did not differ significantly from barley in length (Table 2). In contrast, PR-B, which was longer and thinner than barley, broke the conveyor belt and, in a small-scale test, paddy rice 102, which was smaller and thinner than barley, also appeared likely to damage the equipment. Because rice kernels are less plump than barley kernels (Table 2; Supp. Fig. 1), some kernels became wedged against the walls of the belt and damaged the equipment. After this the rice was transported into the steeping vessel either manually or pneumatically. This was an important observation as most modern malting equipment is designed for barley, and since the transporting issue seemed to be varietal-specific, identifying rice varieties with similar morphology to barley (e.g. same length as barley, 8.5 mm, Table 2) that are suitable for transport using preexisting systems and do not wedge themselves would be beneficial as no extra capital would be required to transition from barley to rice.

Several rice malting procedures were performed to adapt the micro-malting process to the pilot-scale equipment and to overcome differences between the two procedures (e.g. lack of vessel rotation and hydrostatic pressure effects at pilot scale) (Supp. Table 3). First, a barley-like malting procedure was tested (steeping at 16 °C); however, little modification was achieved, as the resulting malt showed limited acrospire growth, poor friability, and a Kolbach index (i.e. the ratio of soluble protein to total protein) of 2.7 (Table 3). The optimised rice malting protocol previously reported [32], with some variations (e.g. extended immersions, warm immersions, and use of gibberellic acid) (Supp. Table 3), was then implemented. Results remained unsatisfactory, with only limited improvement in overall modification, even though some trials were excessively long and economically unrealistic (e.g. a 9-day germination).

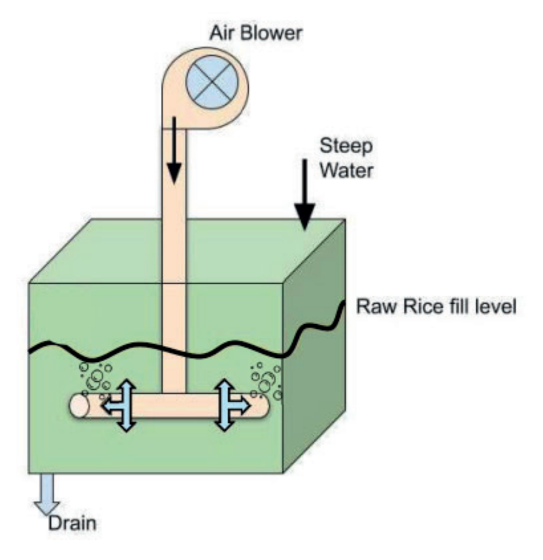

Fig. 2 **Schematic of a steeping and malting vessel used to germinate rice in malthouse B**

Table 4 Malting losses, enzymatic activity, extract, and real degree of fermentation (RDF) of malted rice.

Malted sample	Malting losses	Run-off	α-amylase	β-amylase	Gluco-amylase	LD	FAN	Fine extract as malt	RDF as base malt	Fine extract as adjunct
	% d.b.		DU/g d.m.	Betamyl/g d.m.	U/kg d.m.	U/kg d.m.	mg/L	% d.m.	%	% d.b.
P2R	10.5$	Good	210	790	578	554	200	81.99	70.65	NA
101-W	7.2	Static	12	4	4573	294	59	63.99	24.65	64.19
102-W	3.6	Static	13	11	4342	1615	57	66.01	32.52	66.91
103-W	9.7	Static	13	18	3132	999	60	37.52	34.74	65.56
103-S	14.2	Good	14	12	2529	401	146	39.02	39.90	59.02
104-S	19.0	Good	19	9	2457	906	110	63.90	42.66	62.74

LD – limit dextrinase. FAN – free amino nitrogen. RDF – real degree of fermentation. $Malting loss observed in barley[54]. P2R is pale two-row barley malt. 101-W, 102-W, and 103-W were winter batches (second malting trial). 103-S and 104-S were summer batches (third malting trial) using opacity as a modification parameter. Specific malting conditions for each batch were shown in Supp. Table 4. Cultivars with multiple batches had the malt mixed prior to analysis.

3.3 Second commercial malting trials – immersion box malting vessels during winter

The rice was then sent to Malthouse B, which uses an immersion tank for steeping and germination (Figure 2) and a drum roaster for drying. Although the tank could receive heated water, the equipment did not provide strong thermal insulation. This is important to note because the initial malting trials took place during an exceptionally cold winter, with outdoor temperatures ranging from -8 to 11 °C. These conditions likely contributed to lower malt modification and longer germination times. Unfortunately, the tank temperature was not recorded, although the malting conditions are provided in Supplementary Table 4. Nonetheless, some shoot growth was observed (Supplementary Figure 4).

The malts MR 101-W, 102-W, and 103-W produced in the second malting trial were evaluated for key malting quality parameters, including FAN, extract as malt and as adjunct, amylolytic enzyme activity, and malting losses (Table 4). With respect to FAN, the more highly modified malted rice produced in the third malting trial (110–146 mg/L; MR 103-S and 104-S) showed values that were 50–66% lower than those of malted barley (200 mg/L), but approximately two- to three-fold higher than those observed in the second malting trial (~60 mg/L; MR 101-W, 102-W, and 103-W). The FAN values obtained in the third malting trial were consistent with those reported in the literature for malted rice (67–191 mg/L) [32]. Previous work has also indicated that malted rice with comparable FAN levels can be used in low-alcohol beer production without generating detectable off-flavours [42].

Regarding the effects of amylolytic enzymes on extract and attenuation, MR 101-W, 102-W, and 103-W showed very slow run-off during extract analysis. The lower degree of modification in the second malting trial may have resulted in reduced amylase activity and an inability to liquefy starch, thereby creating a viscous, gel-like wort. The extract values obtained when these samples were used as malt or as adjunct were similar for MR 101-W, 102-W, and 104-S, indicating that the starch could be properly solubilised. However, the low fermentability observed when the samples were used as malt (<45%) indicates that malted rice requires exogenous enzymes for effective saccharification. MR 103-W and 103-S showed much lower extract when used as malt than when used as adjuncts, which may be due to polyphenol–enzyme–starch interactions [56] and inhibition of amylolytic enzymes [57], especially α-amylase and glucoamylase.

To further explore the potential of malted rice as an adjunct, given that rice has historically been used by brewers in milled form [10], high-gravity worts containing 40% and 60% inclusion of either malted rice or milled rice were produced using malted barley together with malted or milled rice from the same variety. Major brewing quality parameters, including wort density, RDF, and FAN, were then measured (Table 5). Malted rice produced wort with ~16–22% (MR 102-W) and ~28–40% (MR 103-W) lower gravity than wort produced from milled rice of the same variety. RDF was also lower for malted rice than for milled rice (~3–15%). These reduced wort gravities and RDF values may reflect the greater amount of non-fermentable material (protein, lipids, and rice hulls) present in malted rice than in milled rice. Nevertheless, despite the lower grain addition in the malted-rice trials, MR 102-W FAN was ~30–45% higher than that of the milled-rice wort.

3.4 First commercial brewing trials – brewing with rice malt from 2nd malting trials

Malted rice samples from the second malting trial, together with a questionnaire (Supp. Table 7), were distributed to four commercial breweries and one research brewery (Table 6) to evaluate industry-scale brewing challenges associated with malted rice. Pilot brews ranged from ~0.6 hL/batch (breweries B, C, D, and E) to 10 hL/batch (brewery A). Although no brewery was instructed on what style to produce, all chose to brew lager-style products with this material. This choice was probably influenced by the perception of rice as a relatively neutral grain in brewing [11].

Brewery A tried to brew with MR 103-W [pigmented, aromatic rice variety] but reported that the malted rice clogged the pipe as the wort was transferred from the mash tun to the lauter tun. Upon further investigation, the brewery reported that the malted rice had not been adequately broken or cracked during milling, probably because industrial mill gaps are larger than those required for malted rice owing to kernel differences (Supp. Fig. 1; Table 2) and possibly lower friability. The brewery therefore requested a more highly modified malted rice for a repeat brew.

Table 5 **Process losses, extract, fermentability, and FAN of milled rice and malted rice.**

Rice sample	Rice quality		Grist composition	Wort Quality		
	Milling/ malting losses [%]	Fine extract as adjunct [% d.b.]	Rice inclusion [%]	Wort OG [oP]	RDF [%]	FAN [mg/L]
Malted 102-W	3.6	62.74	40	13.69	69.1	279
			60	12.82	71.8	266
Milled 102	29.3	79.52	40	16.25	81.9	208
			60	16.58	85.8	183
Malted 103-W	9.7	65.56	40	11.66	71.1	266
			60	9.75	80.4	188
Milled 103	30.5	77.99	40	16.22	72.9	269
			60	16.15	86.6	179

Extract % d.b. – extract percentage in dry basis. Extract % paddy rice d.b. – extract percentage in dry basis of paddy rice equivalent (accounting for milling or malting losses). Paddy rice equivalent inclusion – percentage of paddy rice equivalent rice in the mixture, the remaining percentage was from malted barley. Wort OG – wort original density; RDF – real degree of fermentation; FAN - free amino nitrogen. Milled rice had <0.5% surface lipid content. Malted rice 102-W and 103-W were produced in malting trial #2. Milled rice 102 and 103 were milled from paddy rice 102 and 103, respectively.

Brewery B reported a pronounced increase in mash viscosity as the temperature approached the gelatinisation range when brewing with MR 102-W, a non-pigmented, non-aromatic rice variety. As the mash reached gelatinisation temperature, unliquefied soluble starch caused a sharp increase in viscosity, resulting in mechanical failure of the mash paddle and a difficult lauter. To prevent this increase in viscosity, α-amylase from exogenous enzymes or from malted barley inclusion at ~10% of the grist bill is required to hydrolyse soluble starch components, including amylose and amylopectin, into smaller dextrins [58]. In a separate trial, the brewery used MR 103-W at a 10% inclusion rate to impart a purple colour. Although the brewery was satisfied with the unique rice pudding, sake, and rice-like flavours and aromas, the overall flavour and aroma intensity were considered too strong for use as a base malt, suggesting that MR 103-W is better suited as a speciality malt. Additionally, the brewery reported less desirable flavour descriptors, including smoke and 4-ethylphenol, which is consistent with findings from Guimaraes and Lafontaine [42], who also observed phenolic notes in pigmented malted rice.

Brewery C aimed to produce an all-malted rice gluten-free beer using MR 103-W, a pigmented, aromatic rice variety, as the base malt. However, extract was extremely low, reaching only 3.7 °P at a 4:1 water-to-grist ratio (WGR), with a brewhouse efficiency of 12.5%. To improve extract yield, the brewery boiled the malted rice and supplemented the mash with exogenous enzymes, which increased wort extract to 7.4 °P and brewhouse efficiency to 38% in the first runnings. The resulting beer exhibited a novel purple colour, and its flavour was markedly different from that of malted barley beer. Compared with beers produced from other malted gluten-free grains, the aroma of the malted rice beer was considered notably improved and was described as toasted almond and rice crackers by the brewers. Because purple colour is not commonly associated with established beer styles, consumers initially showed some hesitation when tasting the beer.

Brewery D made a lager using MR 101-W [non-pigmented, aromatic rice variety] as an adjunct. A pregelatinisation step and proper saccharification prevented mashing and fermentation issues. As with other malted rice samples, MR 101-W contributed a distinctive nutty character that was well received by consumers.

Table 6 **Characteristics of the breweries and how they utilised malted rice in their brews.**

Brewery	Size	Pilot brewery	Malted rice	Use in recipe	Style brewed
A	Regional brewery	11.7 hL	103-W & 103-S	Adjunct	Helles Lager
B	Regional brewery	0.59 hL	102-W & 103-W	All-malt	Lager
C	Brewery	0.59 hL	103-W	All-malt	Lager
D	Brewery	5.9 hL	103-W	Adjunct	Lager
			102-W	Adjunct	Lager
E	Nano-brewery	0.59 hL	104-S	All-malt	Non-alcoholic lager

Brewery size was defined as large brewery (>7,150,001 hL), regional brewery (18,001–7,150,000 hL), brewery (6,001–18,000 hL), microbrewery (601–6,000 hL), and nanobrewery (<600 hL). An adjunct brew used malted barley in addition to malted rice, whereas an all-malt brew used only malted rice. Malted rice 101-W was aromatic and non-pigmented; 102-W was non-aromatic and non-pigmented; 103-W and 103-S were aromatic and pigmented; and 104-S was non-aromatic and non-pigmented. Brewery D was a partnership between two breweries. Non-alcoholic lager contained <0.5% alcohol by volume.

To overcome the viscosity challenges described above and to make malted rice more practical for craft brewers, Brewery E used MR 102-W [non-pigmented, non-aromatic rice variety] at 30% of extract in a two-vessel system (mashing-lauter tun and boiling tun). The malted rice was mashed at 66 °C at a 4:1 WGR, the temperature was then increased to 80 °C, and exogenous heat-stable α-amylase was added to support starch liquefaction and saccharification as the starch gelatinised. Water at 55 °C was then added to reduce the mash temperature to 64 °C before the malted barley was added while maintaining a 4:1 WGR. The original wort gravity (OG) was 11.46 °P, and fermentation with Fermentis W-34/70 yielded a beer with 5.10% alcohol by volume (ABV) and 69.31% RDF, which was in line with benchtop trials (Supp. Table 5). The wort showed good run-off and low viscosity, and the resulting beer was described as neutral, clean, and highly drinkable, with no off-flavours. This approach demonstrated that craft breweries can pre-gelatinise adjuncts using a single mash vessel.

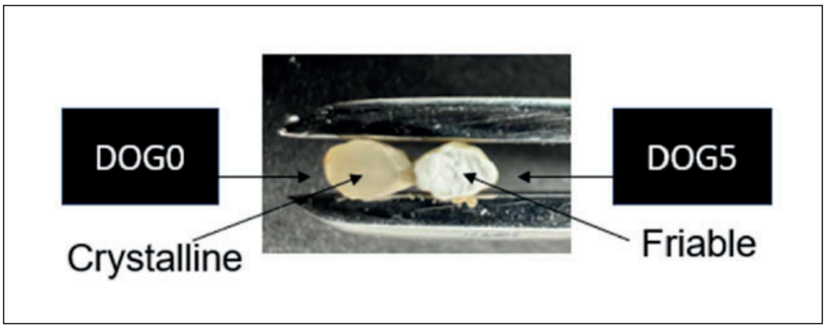

Fig. 3 **Visual transition in the endosperm in cross-sections taken at 0 and 5 days of germination (DOG). Under-modified kernels exhibit a glassy, crystalline endosperm, whereas properly modified and over-modified kernels are opaque and friable**

Several breweries reported complications with milling, and it is well established in barley malting that malt modification, milling, and particle size strongly influence extract yield [20]. To investigate this further, the effects of milling on particle size, extract, and fermentability were evaluated. The largest mill gap (1.55 mm) resulted in the lowest extract (39.62%) and attenuation (24.12%), likely because of uncracked grains (Supp. Fig. 5), whereas mill gaps of 0.95 and 0.50 mm produced the highest extract and attenuation (~57% and ~30%, respectively) (Supp. Table 6). The relatively low attenuation of malted rice compared with previous results [32] was likely due to under-modification. Although this limits its performance as a base malt, particularly for MR 103-W, pigmented malted rice still showed strong potential as a speciality grain for contributing novel colour and aroma attributes. In addition, under-modified malted rice combined with exogenous enzymes may be useful for non-alcoholic beer production because its higher proportion of larger dextrins could provide greater body and viscosity with less sweetness.

Although brewers reported that the second-trial malted rice was under-modified and lacked friability, the resulting beers still exhibited novel and desirable sensory attributes. In particular, the brews were perceived as less aldehydic than malted barley beers, suggesting a reduction in typical “worty” off-flavours, consistent with observations by Schubert, et al. [59] for milled rice. These findings highlight the potential of malted rice to contribute distinctive flavour profiles and support innovation in the craft brewing industry, even when malt quality is not yet fully optimised. At the same time, the unique physical and biochemical characteristics of rice, including its smaller kernel size, lower endogenous enzymatic activity, and high proportion of hull material, presented practical processing challenges at scale. These challenges may require dedicated milling equipment or mill adjustments, supplementation with exogenous enzymes to improve process throughput and reduce viscosity-related issues, and modifications to grain-out systems or grist composition, such as the use of dehulled or milled malted rice. Overall, these initial results demonstrated that malted rice is a promising brewing raw material, but further work was needed to optimise rice varieties for malting performance, enzyme potential, and starch functionality.

3.5 Third commercial malting trial – immersion box malting vessels during summer

Concurrently with the first brewing trials, a rice-specific parameter for evaluating grain modification was developed. Traditional malting relies on shoot length typically 75% of kernel length [1]. However, rice shoot growth is much more pronounced, and applying a barley-based standard resulted in under-modified malted rice during the second malting trials. Examination of germinating rice showed that the kernels underwent a distinct transition in the endosperm. Cross-sections revealed that under-modified kernels exhibited a glassy, crystalline endosperm, whereas properly modified grain displayed an opaque and friable endosperm (Figure 3). Further studies should evaluate how this visual change in the endosperm relates to starch structure and enzymatic activity in malted rice.

The third malting trial followed this newly identified parameter and successfully produced properly modified malted rice. The two varieties chosen were 103 and 104, with 104 selected as a variety similar to 102. The higher steeping and germination temperatures (25 °C and 21 °C, respectively) could be readily maintained during summer and allowed the use of a 24 h submerged steep with 1 g of GA and only 4 days of germination with rinse/drain cycles (Supp. Table 4). This procedure reduced steeping and germination time by 75% and 50%, respectively, while still producing fully modified malted rice. However, 103-S was observed to lose pigmentation during each wet cycle in steeping and/or germination, as the steep-out water was purple. Future studies should evaluate germination methods with fewer wet cycles to avoid pigment loss.

The germination qualities of these two batches were measured (Table 4). Malting losses were higher and reflected greater grain development than in the previous batches (MR 102-W and 103-W), despite the shorter germination time. Nevertheless, MR 103-S and 104-S showed extract and fermentability values that were similar

Table 7 **Coarse extract, attenuation, and alcoholic content of malted rice 104-S with different addition of thermostable α-amylase and pullulanase (Ceremix Flex®).**

Enzyme addition	Coarse extract	Apparent attenuation	Real degree of fermentation	Alcohol by volume
[ppm]	[% d.b.]	[%]	[%]	[%]
No enzyme	65.01	46.04	42.66	2.14
625	66.93	52.54	45.52	2.22
1250	67.21	55.67	48.03	2.35
2500	67.10	64.82	54.86	2.66
5000	67.45	73.41	61.08	2.83

% d.b. is percentage dry-basis.

to or higher than those of MR 103-W and 102-W, respectively. MR 103-S and 104-S also exhibited good run-off, with filtration times similar to those of barley malt. These results suggest that summer production conditions may be more favourable for rice malting, whereas colder periods may be better suited to barley malting, potentially allowing commercial malthouses to benefit from seasonal production rotation.

Extract (65%) and fermentability (42%) remained lower in malted rice than in barley (~80%) [51]. Therefore, exogenous heat-stable α-amylase and pullulanase were added to assess whether these characteristics could be improved (Table 7). Apparent degree of fermentation (ADF) increased from 46.04% to 73.41%, and RDF increased from 42.66% to 61.08%. The relatively stable coarse extract supports the claim that properly modified malted rice is self-saccharifying [32]; however, the increase in ADF and RDF showed that the current malted rice lacked sufficient diastatic power to break down dextrins into fermentable sugars (e.g. glucose, maltose, and maltotriose). Therefore, the addition of exogenous enzymes is recommended when working with alternative malted grains until varieties can be developed or bred with sufficient amylolytic capacity and/or starch properties that allow proper saccharification.

3.6 Second commercial brewing trials – brewing with rice malt from 3^rd^ malting trials

The second brewing trials were carried out using the two malted rice samples produced in the third malting trial, which were properly modified. The breweries that conducted second brewing trials were Brewery A with MR 103-S and Brewery E with MR 104-S.

Brewery A repeated the brew using MR 103-S [pigmented, aromatic rice variety] as an adjunct. A dedicated mill was purchased to ensure proper milling, and no issues occurred during the brew. One challenge reported, however, was that the purple colour faded to a brownish hue. The purple colour is related to the anthocyanin content of the malt. As noted above, the extended steeping and germination may have washed out some of these compounds. Further studies are needed to determine how best to germinate pigmented varieties while preserving colour. Malted rice extract remained much lower than that of standard speciality malts, leading to lower wort density and, consequently, reduced ability to achieve extract targets. The low extract of pigmented malted rice required larger quantities of raw material and, consequently, either dilution in the mash tun and/or an inability to produce high-gravity brews. Optimising malting and brewing practices, as well as breeding for higher extract or developing novel products (e.g. syrup), could create additional opportunities for brewery use. Another major drawback reported by this brewer concerned the automated grain-out system. The excess rice hulls could not be removed by the automated grain-removal system, so the brewer had to resort to manual removal. Again, this highlights that implementing a new raw material can create unforeseen challenges. Nevertheless, the brewer noted that malted rice could offer brewers a new set of colours, flavours, and options for innovation.

Brewery E produced an all-malt rice non-alcoholic beer using exogenous enzymes, as well as a 50:50 blend of MR 104-S [non-pigmented, non-aromatic rice variety] and milled rice for non-alcoholic beer production. The 100% MR wort was split between two fermentation vessels to evaluate the effect of dry hopping at 3 g/L. The non-dry-hopped beer was reported to have some metallic taste and astringency, which were not observed in the dry-hopped beer. The metallic taste and astringency may have originated from polyphenols in the rice hulls, although further studies are needed to confirm the source of these off-flavours.

4 Conclusions

Malted rice remains a novel brewing ingredient, and this study highlights several of the key challenges commercial malthouses and breweries must address to successfully integrate it into production. Relative to barley, rice required more intensive steeping and germination conditions to achieve adequate modification. Notably, visual endosperm modification was a more reliable indicator of rice malt quality than acrospire length. Proper modification improved friability, enzymatic activity, extract yield, and fermentability, providing a practical metric that maltsters may use to better control rice malting and potentially adapt to other grains. Additional work is still needed to optimize industrial-scale processing, including shorter steeping cycles, flooded germination, gentler drying conditions to preserve enzyme activity, and shorter mash regimes to improve throughput and ease of production.

From the brewing perspective, malt modification strongly influenced millability, extract yield, and attenuation. A dedicated mill may be needed to process malted rice more effectively, although adjunct gelatinization and saccharification were successfully conducted in the same mash vessel. This approach could allow craft breweries to use ungelatinized starch sources without major capital investment. Importantly, beers produced with malted rice displayed distinctive aroma and flavour characteristics not found in malted barley and were perceived as more appealing than beers made from other alternative malts.

Supplemental Information

Supporting information is provided in a supplementary document containing Supplemental Figures 1 to 5 and Supplemental Tables 1 to 7. This material includes rice and barley size (Supp. Fig. 1), rice chitting and acrospire development (Supp. Fig. 2), a water uptake curve (Supp. Fig. 3), rootlet and acrospire growth across days of germination (DOG) 3, 4, and 5 (Supp. Fig. 4), and ground malt at different mill gaps (Supp. Fig. 5). It also includes water uptake after 24 h (Supp. Table 1) and 72 h (Supp. Table 2) under different conditions; malting conditions for the first trials in cylindroconical vessels (Supp. Table 3) and for the second and third trials in immersion box vessels (Supp. Table 4); comparison of malted rice and milled rice with respect to extract and fermentability (Supp. Table 5); particle size distribution at different mill gaps (Supp. Table 6); and the questionnaire sent to brewers to evaluate operational hurdles and collect feedback (Supp. Table 7).

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Declaration of interest statement

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

AI Statement

The authors used ChatGPT (OpenAI, San Francisco, CA, USA) and Gemini Pro (Google, Mountain View, CA, USA) during manuscript preparation to improve grammar, clarity, and readability. The tool was not used to generate data, perform analyses, or independently interpret results. All scientific content, conclusions, and final wording were reviewed and approved by the authors, who take full responsibility for the manuscript.

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Supplementary Data

Fig. 1 **Malted pale two-row barley (P2R) and malted rice 101-W, 102-W, and 103-W and their dimensions**

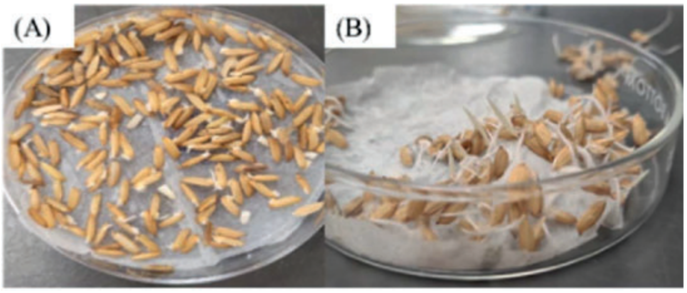

Fig. 2 **Chitting (A) and acrospire growth (B) in rice kernels in the first and third days of germination, respectively**

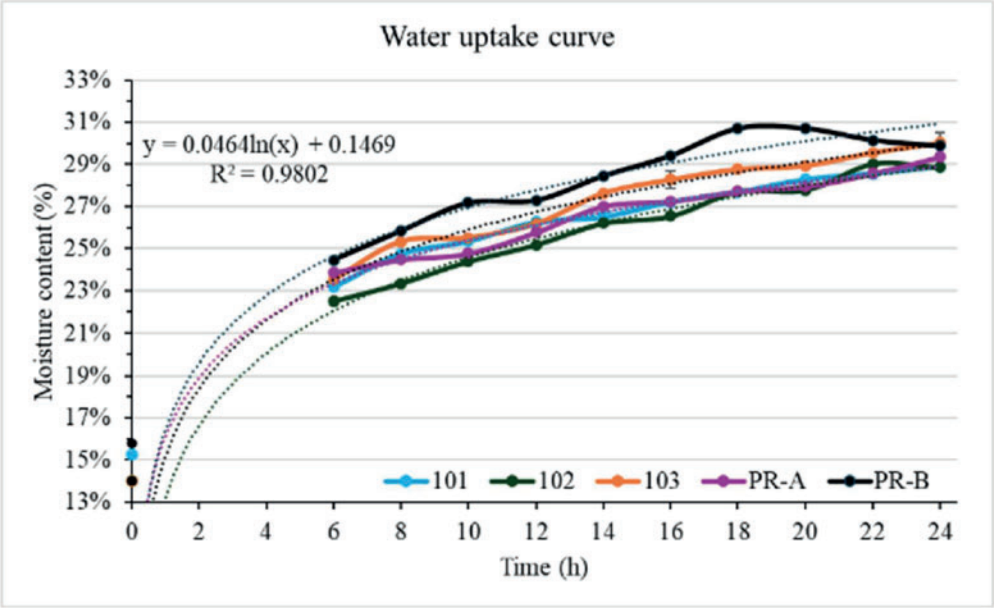

Fig. 3 Water uptake curve (solid line) for paddy rice 101 (blue), 102 (green), 103 (orange), PR-A (purple), and PR-B (black). Dotted curves stand for water uptake logarithmic regression curve for the associate color rice variety. Regression values for 103 were shown

Fig. 4 Rootlet and acrospire growth for days of germination (DOG) 3, 4, and 5

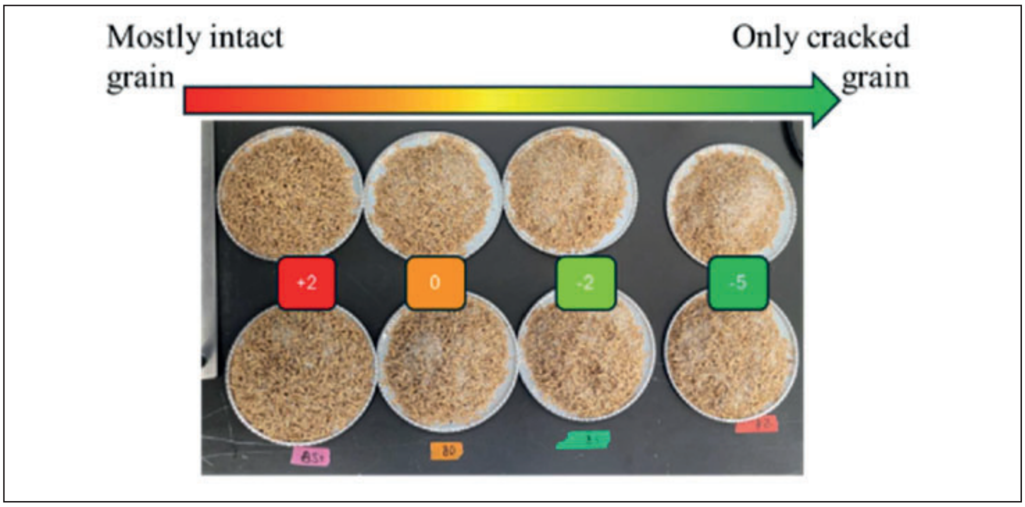

Fig. 5 Ground malted rice at milling gaps +2 (1.55 mm), 0 (1.25 mm), -2 (0.95 mm), and -5 (0.50 mm) that passed through US Standard sieve #10 (2.000 mm). Sieve was used to remove excess husks and better visualisation of cracked grains

Table 1 **Water uptake after 24 h steeping in different water qualities in PR-B**

Condition	pH	Original moisture content (%)	Final moisture content (%)
MilliQ Water	6.95	13.51	29.9a
Brewing water	7.74	13.51	29.8a
Brewing water + $CaCO_3$	8.23	13.51	29.4a
Brewing water + NaOH	9.43	13.51	29.1a

Table 2 **Water uptake after 72 h steeping in different water qualities for PR-A**

Water hardness	Aeration	Steep-out moisture (%)
Soft	No	36.84a
Soft	Yes	39.68a
Hard	No	37.50a
Hard	Yes	38.00a

Values not sharing a group (superscript letter) are statistically different at α=0.05 according to Tukey's test. Soft water was reverse osmosis water at 115-120 ppm of total dissolved solids (TDS). Hard water was city water at 606-652 ppm TDS. Steep-out moisture was calculated as the moisture after steeping continuously for 72 h at 24 oC followed by 24 h of drain. Calculated using Eq. (1).

Supplemental Table 3. Specific malting conditions for malting trials at malthouse A

Treatment	Variety	Steep Temperature (°C)	Steep Profile	Steep immersions/air rest	Spray steep	Steep Temperature (°C)	Total germination time (h)	Germination water additions (L)	Gibberellic acid
Cold, short steep; 5 day germ	101	13	15-hr immersion + 28-hr spray steep	15-hour immersion	28-hour spray steep. Short bursts: on for 5 minutes, off for 60 minutes. Long bursts: on for 45 minutes, off for 5 hrs 15 minutes. 5 total long bursts, 27 total short bursts	19 on days 1-2; 20 on days 3-4	96	6.6 L at hours 20 h, 25 h, 30 h, 35 h, 40 h, 50 h	None
Warm long steep (80hrs spray steep)	102	25	16-hr immersion + 56-hr spray steep	16-hour immersion	56-hour spray steep. Short bursts: on for 5 minutes, off for 60 minutes. Long bursts: on for 45 minutes, off for 5 hrs 15 minutes. 10 total long bursts, 54 total short bursts	22	120	6.6 L at hours 6 h, 12 h, 18 h, 24 h, 30 h, 36 h, 42 h, 48 h	None
No change	104	25	Multiple (4) immersion	8-hr immersion, 16-hr air rest, 8-hr immersion, 16-hr air rest, 8-hr immersion, 12-hr air rest, 8-hr immersion	short burst sprays during air rests, 5 min spay every 60 mins for a total of 41 short bursts	22	159	3.8 L at 8 h and 20 hours; 6.6 L at 30 h, 40 h, 50 h, 60 h, and 3.8 L at 70 h and 80 hours	None
VLB steep (80hrs) + GA, 9 day germ (warm)	105	25	Multiple (4) immersion	16-hr immersion, 8-hr air rest, 16-hr immersion, 8-hr air rest,12-hr immersion, 12-hr air rest, 12-hr immersion	short burst sprays during air rests, 5 min spay every 60 mins for a total of 25 short bursts	24	214	3.8 L at 10 hours; 5.7 L at 20 h, 30 h, 40 h; 3.8 L at 50 h, 60 h, 70 h, 80 h	10 h into germination at 1.92 g/L of water
Extra long immersions (56/84 hrs), 6 day germ, Dbl GA	101	25	Multiple (4) immersion	16-hr immersion, 8-hr air rest, 16-hr immersion, 8-hr air rest,12-hr immersion, 12-hr air rest, 12-hr immersion	short burst sprays during air rests, 5 min spay every 60 mins for a total of 25 short bursts	23	120	3.8 L at 10 h and 20 h; 5.7 L at 30 h, 40 h, 50 h, 60 h; 3.8 L at 70 h and 80 h	10 h and 20 h into germination at 1.92 g/L of water

Table 4 **Specific malting conditions for each malting trial batch at malthouse B**

Variety	Malting trial	Batch number	Paddy rice weight	Paddy rice moisture	Malted rice weight	Malted rice moisture	Gibberellic acid	Steeping procedure	Total steeping time	Germination	Total germination time	Kilning (drum roll)	Malting losses	Malting losses
Unit			kg	% wb	kg	% wb			h		h		% wb	% db
101-W	2	1	181	14.8	150	4.2	1 g at the 1st steeping rest	24 h steep, 2 h air rest, 21 h steeping, 1.5 h	48.5	120 h	120	83 min at 65 oC, 24 rpm; 95 min at 20 oC, 24 rpm	17.5	7.2
102-W	2	1	181	13.5	157	3.0	1 g at the 1st steeping rest; 1 g at the 1st steep during germination	16 h steep, 8 h air rest (3 x), 16 h steep	88.0	32 h germination, 16 h steep, 32 h germination, 16 h steep, 176 h	272	53 min at 30 oC, 24 rpm; 2.25 h at 80.4 oC, 24 rpm	13.5	3
102-W	2	2	181	13.5	155	3.0	1 g at the 1st steeping rest; 1 g at the 1st steep during germination; 1 g at the 2nd steep during germination	17 h steep, 8 h air rest, 22 h steep, 8 h air rest, 16 h steep, 8 h air rest, 17h steep	96.0	32 h germination, 10.2 h steep, 13.8 h germination, 2.35 steep, 21.65 h germination, 16 h steep, 8 h germination, 80 h germination	176	61 min at 22 oC, 24 rpm 88 min at 84.9 oC, 24 rpm	13.5	3
103-W	2	1	181	13.5	147	3.3	1 g at the 1st steeping rest; 1 g at the last steep	96 h steep	96.0	168 h	504	51 at 14.6 oC, 24 rpm; 50 min at 75.4 oC, 24 rpm; 37 min at 86.2 oC, 24 rpm	19	9.4
103-W	2	2	159	13.5	128	3.3	1 g at the 1st steeping rest; 1 g at 144 h of germination	18 h steep, 6 h air rest (3x), 18 h steep	90.0	504 h	504	71 min at 16.6 oC, 24 rpm; 48 min at 85.4 oC, 24 rpm	19.4	9.9
103-S	3	1	181	13.5	138	4.1	1 g at the 1st steeping rest	24 h steep, 24 h air rest	48.0	96 h with rinse/drain cycles every 24 h	96	155 min at 34.5 oC, 24 rpm; 201 min at 75 oC, 24 rpm;	23.8	14.2
104-S	3	1	190	14.8	136	4.3	1 g at the 1st steeping rest	25 h steep, 23 h air rest	48.0	96 h with rinse/drain cycles every 24 h	96	52 min at 46.5 oC, 24 rpm; 86.1 min at 86.1 oC, 24 rpm;	28.6	20
104-S	3	2	181	14.8	142	4.7	1 g at the 1st steeping rest	24 h steep, 24 h air rest	48.0	96 h with rinse/drain cycles every 24 h	96	75 min at 42.75 oC, 24 rpm; 135 min at 76.6 oC, 24 rpm;	21.8	12.7
104-S	3	3	181	14.8	127	4.8	1 g at the 1st steeping rest	24 h steep, 24 h air rest	48.0	144 h with rinse/drain cycles every 24 h	144	155 min at 42.75 oC, 24 rpm; 201 min at 76.6 oC, 24 rpm;	24.3	32.2

Table 5 **Process losses, extract, fermentability, and free amino nitrogen (FAN) of milled rice and malted rice**

Rice sample	Rice quality		Grist composition	Wort Quality		
	Milling/ malting losses	Fine extract as adjunct	Rice inclusion	Wort OG	RDF	FAN
	[%]	[% d.b.]	[%]	[oP]	[%]	[mg/L]
Malted 102	3,6	62,74	40	13,69	69,1	279
			60	12,82	71,8	266
Milled 102	29,3	79,52	40	16,25	81,9	208
			60	16,58	85,8	183
Malted 103-W	9,7	65,56	40	11,66	71,1	266
			60	9,75	80,4	188
Milled 103	30,5	77,99	40	16,22	72,9	269
			60	16,15	86,6	179

Extract % d.b. is the extract percentage in dry basis.
Wort OG is wort original density.
RDF is real degree of fermentation.
Milled rice had <0.5% surface lipid content.
Malted rice 102-W and 103-W were produced in the second malting trial.
Milled rice 102 and 103 were milled from paddy rice 102 and 103, respectively.

Table 6 **Particle size distribution, extract, and forced attenuation of malted rice 102 for different mill gaps**

Mill setup	Mill gap	Particle size distribution (%)						Extract	RDF
	(mm)	≥ 2.380 mm	1.680 mm	1.000 mm	0.841 mm	0.250 mm	< 0.250 mm	(% d.b.)	(%)
2	1,55	55,76	24,79	15,41	1,15	2,32	0,58	40.65c	25.33b
0	1,25	27,79	23,73	37,8	3,08	6,39	1,19	54.41b	25.42b
-2	0,95	11,41	20,58	51,53	5,56	8,69	2,23	58.27b	26.80b
-5	0,5	2,53	10,63	49,6	11,13	22,15	3,97	57.16b	27.94b
Fine grind	Cyclone mill	0	0	0	0	39,44	60,56	64.33a	32.52a

The real degree of fermentation (RDF) was measured through forced fermentation. Values not sharing a group (superscript letter) are statistically different at α=0.05 according to Tukey's test.

Table 7 Survey distributed to brewers about their perception on using malted rice as a novel brewing ingredient

c	Question	Type of Answer	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options
Informed Consentment Agreement	"Project Number: IRB Protocol 2503597950 Investigators: Scott Lafontaine, Department of Food Science University of Arkansas, 2650 North Young Avenue Fayetteville, AR 72704, phone #: 479-789-3292, email: Scottla@uark.edu Product Evaluated: Rice malt Description: The purpose of this data collection and survey is to assess the opinions of consumers and professionals about making and consuming rice and different grain-based beverages. Throughout the survey, you may be asked a range of different questions to evaluate purchasing intent of the different grain based beverages, you . Demographics will also be collected to evaluate the make-up of the audience. Upon completion of the survey your data will be aggregated with the data from the other participants and processed. The total estimated time to complete the survey will be ~10-20 min Risks and Benefits: Benefits will be seen in future improvements in beer quality from producers and ingredient distributors. If you provide an email, we will share the data/ results as soon as we can process them. You will also be entered into a raffle receive a gift card of $15 per hour. Confidentiality: Only the researchers will know your name and all information will be kept confidential to the extent allowed by law and university policy. Results from the research will be reported as aggregate data. Right to Withdraw and not participate: Your participation in this research is completely voluntary. You are free to refuse to participate in the research and to withdraw from the survey at any time without penalty Compensation: For your participation in this panel, you will be entered into a drawing for 5 in the form of a $15 gift card per hour. Compensation will be distributed at the end of the panel and only individuals who participate in every session and have completed the entire panel will receive this compensation."								

Continued table 7

c	Question	Type of Answer	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options
Informed Consentment Agreement	"I, have read the above description, including the purpose of the data collection, the procedures to be used, the potential risks and side effects, the confidentiality, as well as the option to withdraw from the survey and study at any time. By agreeing to participate in the survey, you are agreeing to willingly participate in this survey, that you are 21 years of age or older, and you regularly consume beers and/ or malt beverages with no ill effect. If you disagree your data will be excluded from the analysis but you can still take the survey."	Multiple choice	I agree	I disagree					
Informed Consentment Agreement	Do you want to be pubicly recognized as a partner in this research?	Multiple choice	Yes, this brewery wants to be recognized for taking part in the research (Insert brewery name below)	No, this brewery wants to stay anonymous	Other (specify)				
Informed Consentment Agreement	Please state your email. Please confirm if email is correct. This will be used for compensation.	Open question							
Demographics Survey	In which US state is your brewery located?	Open question							
Demographics Survey	Which range best describe your brewery's size/annual production value?	Multiple choice	Nanobrewery (<500 bbl/ <600 hL)	Microbrewery (501-5,000 bbl/ 601-6,000 hL)	Brewery (5,001-15,000 bbl/ 6,001-18,000 hL)	Regional brewery (15,001-6,000,000 bbl/ 18,001-7,150,000 hL)	Large non-craft brewery (>6,000,001 bbl/ >7,150,001 hL)		
Demographics Survey	Can you perform pilot system batch size?	Multiple choice	Yes	No					
Demographics Survey	What is the size of your pilot system (please indicate whether bbl or hL)	Open question							
Demographics Survey	What equipment do you use? Check all that apply.	Multiple choice	Single-vessel equipment	Mashing tun	Lauter tun (not associated with mashing tun)	Boil tun	Whirlpool	Bright tank	Other(s)

Continued table 7

c	Question	Type of Answer	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options
Demographics Survey	Can your pilot system perform step mashing?	Multiple choice	Yes	No					
Milling and Mashing	How did you use the rice malt?	Multiple choice	All-malt	Adjunct (with barley malt)					
Milling and Mashing	What variety was used in this trial? Check all that apply.	Multiple choice	Malted rice #101 (aromatic, non-pigmented)	Malted rice #102 (non-aromatic, non-pigmented)	Malted rice #103-W (aromatic, pigmented)	Malted rice #103-S (aromatic, pigmented)	Malted rice #104 (non-aromatic, non-pigmented)		
Milling and Mashing	What beer style(s) or product best describe(s) your brew with malted rice?	Open question							
Milling and Mashing	What was the grist composition in regards to malted rice? (%)	Open question							
Milling and Mashing	Milling type	Multiple choice	Roller mill (Please indicate 2-, 4-, or 6-row)	Hammer mill					
Milling and Mashing	Compared to barley, how was the milling performed?	Multiple choice	Same as barley malt	Same as milled rice	Adapted for malted rice (e.g., adjusted distance, multiple passes)	Other/ More than once			
Milling and Mashing	Was the brewing water treated?	Multiple choice	Yes, salt	Yes, acid	Yes, other	No	Not applicable/Do not want to share		
Milling and Mashing	What was the mashing procedure? Please state time and temperature for each rest or NA for not sharing.	Open question							
Milling and Mashing	Did the measured extract match the expected extract?	Multiple choice	Yes, as expected	No, measured extract was lower	No, measured extract was higher				
Milling and Mashing	How different was the expected extract from measured extract?	Open question							
Fermentation & Lagering	What was the fermentation profile? I.e., type of yeast (lager, ale, belgian, wheat), temperature, time, oxygenation rate. NA for not sharing.	Open question							

Continued table 7

c	Question	Type of Answer	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options
Fermentation & Lagering	The fermentation was	Multiple choice	Shorter than usual	Similar to usual	Longer than usual				
Fermentation & Lagering	Was there lagering after fermentation? If so, how long? NA for not sharing.	Open question							
Fermentation & Lagering	The diacetyl rest was	Multiple choice	Shorter than usual	Similar to usual	Longer than usual	Not performed	Not sharing		
Fermentation & Lagering	Was the alcohol production as expected?	Multiple choice	Yes	No					
Beer Characteristics	How is foam retention when using rice?	Multiple choice	Very poor retention	Poor retention	Neither poor nor good retention	Good retention	Very good retention		
Beer Characteristics	How would you classify the foam formation (ability to create CO2 and foam)? Please do not evaluate the foam stability (how long the foam takes to collapse).	Multiple choice	Good formation	Poor formation	No foam formation	Beverage was not carbonated	Other (specify)		
Beer Characteristics	How would you classify the foam stability (time for the foam to collapse)?	Multiple choice	Very unstable	Unstable	Neither stable nor unstable	Stable	Very stable	Beverage was not carbonated	
Beer Characteristics	How would you classify the beer color?	Multiple choice	Darker than expected	As expected	Lighter than expected	Other (specify)			
Beer Characteristics	How would you classify the clearness of the beer?	Multiple choice	Turbid	Clear	Other (specify)				
Beer Characteristics	Did the beer present solid/flocculent material? Specify what kind of material if applicable.	Multiple choice	Yes	No					
Malted rice sensorial attributes	How would you classify the aroma intensity?	Multiple choice	Very low	Low	Just right	Intense	Very intense		
Malted rice sensorial attributes	How would you classify the aroma? Check all that apply.	Multiple choice	Good (specify)	Bad (specify)	Neither good nor bad (specify)				
Malted rice sensorial attributes	How would you classify the flavor intensity?	Multiple choice	Very low	Low	Just right	Intense	Very intense		

Continued table 7

c	Question	Type of Answer	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options	Answer options
Malted rice sensorial attributes	How would you classify the flavor? Check all that apply.	Multiple choice	Good (specify)	Bad (specify)	Neither good nor bad (specify)				
Malted rice sensorial attributes	How was the mouthfeel? Check all that apply.	Multiple choice	Thin body	Thick body	Astringent	Metallic	Other(s) (specify)		
Overall Evaluation	Would you consider using malted rice again on a larger scale?	Multiple choice	Yes	No	Prefer not to say				
Overall Evaluation	Would you modify your recipe to better use malted rice? - Selected Choice	Multiple choice	Yes (specify)	No	Prefer not to say				
Overall Evaluation	How would you overall rate this product for: - Overall usability	Line scale							
Overall Evaluation	How would you overall rate this product for: - Overall flavors	Line scale							
Overall Evaluation	How would you overall rate this product for: - Overall rating	Line scale							
Overall Evaluation	What did you like most about this product?	Open question							
Overall Evaluation	What did you dislike most about this product?	Open question							
Overall Evaluation	Other comments	Open question							