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A cooking and eating quality evaluating system for whole grain black rice

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Abstract
Black rice has a long history of cultivation in Asia especially China. As a whole grain, black rice is rich in diverse nutrients including proteins, vitamins, amino acids, minerals, unsaturated fatty acids, dietary fibers, alkaloids, carotenes, phenolic compounds, and anthocyanins, in addition to starch. Many studies have demonstrated a range of health-promoting effects by black rice, which has greatly attracted the attention of consumers. However, the production and consumption of black rice has been low mostly because of its poor cooking and eating quality. To address this problem, the first is a need for technology to evaluate the cooking and eating quality of black rice. In this study, we investigated the feasibility of using Rice Taste Evaluation System (RTES) as a proxy approach to eating and cooking quality evaluation of whole grain black rice (WGBR). Totally, 775 black rice samples obtained from 363 accessions harvested from field planting were evaluated both with sensory evaluation by panelists and with RTES consisting of a cooked rice taste analyzer and a hardness and stickiness meter, which produced 8 characteristic parameters. We obtained highly significant correlation ($R^2 = 0.867$, $P < 2.2 \times 10^{-16}$) between sensory test scores and RTES values by multiple linear regression equation based on the selected variables, which was validated with just as high correlation, indicating that the RTES can provide equivalent results the sensory test. With the efficiency of this equipment, the RTES can provide a convenient and accurate tool for high throughput evaluation of cooking and eating quality of WGBR for breeding and other usages.

Keywords Cooking and eating quality · Whole grain black rice · Rice taste evaluation system · Sensory test · Regression equation

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Introduction

Traditionally, rice grain quality is defined mainly based on the taste of fine milled rice, known as cooking and eating quality, plus some other properties such as appearance quality and processing quality (Juliano 1985). This quality pursuance has provided the basis and consensus for quality evaluation in the international rice market, although different human populations may prefer different characteristics of the rice grains (Juliano and Villareal 1993). Consequently fine taste of cooked rice has been a common goal of many rice breeding programs (Butardo et al. 2019), this has been especially the case in rice breeding of recent decades in China.

It has become increasingly aware that fine milled grains including rice as staple food cause a range of health hazards by escalating the incidences of many noncommunicable diseases such as metabolic syndrome, diabetes mellitus, cardiovascular diseases, cancers as well as other health conditions (GBD 2017 Diet Collaborators 2019; The WCOTROCHADIC 2023). Therefore, nutrition and health experts have advocated to consume whole grain instead of fine milled/polished grain as staple foods, including rice and other cereals. This is not only because whole grain supplies rich and balanced nutrients, but also consumption of whole grains is beneficial for resource and environmental sustainability in food production (Willett et al. 2019). Studies based on large human cohorts have shown that adequate consumption of whole grain is associated with greatly reduced risk of many health problems including cardiovascular diseases, cancer, all cause and cause specific mortality (Aune et al. 2016).

Black rice is a typical whole grain with a long cultivation history in Asian countries especially China. This rice is black due to a pigment known as anthocyanin in the pericarp. Whole grain black rice (WGBR) consists of pericarp, seed coat, aleurone, embryo (these four layers were collectively known as bran), and endosperm (Fig. S1). The bran layer is rich in dietary fiber, protein, functional lipids, vitamins, minerals, anthocyanins, phenolic compounds, oryzanols, and many bioactive compounds (Sedeek et al. 2023), while fine milled/polished rice has mainly starch, a small amount of protein and trace amounts of a few other nutrients. Moreover, consumption of WGBR increases the edible part of rice by at least 20%, which would greatly reduce the pressure on the production side thus better secure food security at reduced environmental costs. To exploit the whole benefits of black rice, Zhang (2021a; b) proposed to make black rice staple food in daily life. Zhang et al (2024) also put forward the concept of steaming and cooking type of whole grain black rice and released a variety with excellent eating and cooking quality. However, the production and consumption of black rice is low, mostly because its poor cooking and eating quality which is the limiting factor to reach the consumers.

To address this problem, the first is a need for developing an efficient and reliable technology to evaluate the cooking and eating quality of WGBR. Eating quality, also referred to as palatability, of rice is comprehensively determined by aroma, appearance, taste and texture. The most direct and reliable method for determining rice eating quality is sensory evaluation, in which a trained panel of ≥ 10 members taste and evaluate cooked rice samples and give scores on the basis of sensory profile (Civille and Szczeniak 1973; Mundo et al. 1989). However, this analysis is labor consuming and also requires a large amount of the rice sample, normally ~ 300 g of dry grain per sample. Thus, this technique is not feasible for large population analysis or high-throughput assessment of early generation materials in breeding programs. Conventionally, rice eating quality is indirectly estimated on a battery of physicochemical measurements including amylose and protein contents, alkali spreading value, amylographic gelatinization and paste viscosity characteristics, and water-uptake capacity. However, they do not capture the full complexity of cooked rice that is perceived by a person (Champagne et al. 2001).

The rice taste analyzer converts various physicochemical parameters of rice into taste score based on correlations between near-infrared (NIR) measurements of key constituents (e.g., amylose, protein, moisture, and fat acidity) and sensory score by panelists (Mikami et al. 2000; Mikami 2009). The analysis is capitalized on the ability that specific visible-near infrared wavelength can discriminate the differences in physical and chemical properties of cooked rice samples. It thus provides a palatability estimation equation based on correlations between a visible-near infrared spectroscopy and sensory test score using a small sample of 30 g cooked rice (Mikami 2009). It was confirmed accurate and efficient in the measurement of cooking and eating quality of Japanese cultivars (Hori et al. 2016; Iijima et al. 2019; Hori et al. 2021). It was also confirmed to predict the eating quality of Chinese *Japonica* (Meng et al. 2010) and *Indica* rice varieties (Lai et al. 2011) quite well. As such analysis can be used for rapid screening using small samples, it has been widely applied to evaluate the eating quality of milled white rice to meet diverse needs (Yang et al. 2013; Zhang et al. 2016; Chen et al. 2021; Shi et al. 2022; Xiong et al 2022; Yuan et al. 2022; Yao et al. 2023).

In this study, we tested the usefulness of the Rice Taste Evaluation System (RTES) consisting of a cooked rice taste analyzer and a hardness and stickiness meter, in eating quality evaluation of WGBR. Totally 775 black rice samples obtained from 363 accessions were evaluated with the RTES and by sensory test with trained panelists. We showed that the RTES may provide a convenient and accurate equipment method for predicting eating quality of WGBR, which may be used in the breeding programs and also for other purposes.

Materials and methods

Rice samples

A total of 363 black rice accessions were collected, with 296 from rice growing areas of China including Yunnan (80), Hubei (83), Hunan (48), Shanxi (35), Shandong (13), Guangdong (11), Zhejiang (5), Jiangsu (4), Hainan (4), Guangxi (3), Anhui (3), Guizhou (3), Jiangxi (2), Fujian (1), Jilin (1), 44 from China National Rice Research Institute, 12 from National germplasm resource bank, unknown (6), and 5 from Japan. The seeds of these accessions included cultivars, germplasm stocks and landraces, and were kindly provided by national germplasm resource bank, agricultural science institutes and seed companies over the country.

For sensory evaluation, rice accessions selected from this collection were planted in two seasons. In the first season, 20 seedlings for each of 326 accessions were planted in the winter nursery of Huazhong Agricultural University, Lingshui County, Hainan Province on November 30, 2020, with one replication; and paddy rice was harvested in the end of April 2021 at maturity. In the second season, 317 accessions were planted in the experimental farm of Huazhong Agricultural University, Wuhan, on May 30, 2021, in two replications with 40 seedlings per replications, and harvested in October at maturity. All the harvested rice was dried naturally to ~ 14% moisture. Paddy rice was dehulled in a hulling machine THU35C (Satake Corp., Hiroshima, Japan), with the bran layers reserved. The WGBR samples were stored in sealed bags at 4℃ for at least four months before sensory and instrumental analyses.

After excluding samples with less than 500 g dehulled grain, also referred to as whole grain, 133 samples from Lingshui with one replication, and 247 samples with two replications and 70 samples with one replication from Wuhan, totaling 697 samples, were used for subsequent analyses.

Preparation for cooked WGBR

In the pre-test experiment, the effect of the amount of water added and soaking time on the taste of different varieties of black rice were investigated. The results showed that there is no significant difference in taste quality at different soaking times (30 min, 1 h, 2 h) for the same amount of rice-to-water weight. In the same soaking time, the difference in taste was significant with different weight ratios of rice to water (1:1.0, 1:1.2, 1:1.4, 1:1.6). We found that soaking for 30 min and a ratio of rice to water of 1:1.4 is a relatively optimal condition for the majority of the samples, and were used in the preparation for cooked WGBR.

To prepare cooked rice, 200 g of whole grain were weighed, rinsed three or four times with water. After rinsing, water was added in an amount of rice-to-water weight ratio of 1:1.4. The samples were soaked for 30 min, after which each sample was cooked for 50 min in an automatic rice cooker (SR-CNK05-W, Panasonic, China) using the "standard program". Immediately after completion, the cooked rice was stirred and held for 10 min. Then approximately 30 g cooked rice of each sample was placed in coded clear plastic cup and presented warm to the panelist. Another 50 g cooked rice was used for instrumental test.

Sensory evaluation

A group of 30–40 candidates who were interested in joining sensory panel were recruited each year. Before training, a simple test including smell, taste, and color sensitivity was conducted to select candidates with necessary physiological sensitivity. The training covered the basics of standard sensory terminology (Table 1), principles of the evaluation (Table S1), cooking practice of WGBR and the evaluation

Table 1 Sensory descriptive properties and definitions used to evaluate cooked whole grain black rice

Properties/attributes	Description
Aroma	Degree to which the grains smelled: none to much, or unpleasant smell
Color	Degree of the color of the grains: brown to darker black
Glossiness	Degree to which the surface of the grains reflects the lights: none to much
Grain integrity	Degree to which the grains broken: none to much
Stickiness	Degree to which the grains adhere to and pack on the teeth during mastication: none to much
Springiness	Degree to which the grains return to original shape after partial compression: none to much
Hardness	Force required to compress the grain with molar teeth: soft to hard
Mouth/throat coating	Degree of coating perceived in the mouth or throat after swallowing: smooth to roughness
Flavor	The overall flavor impact perceived during mastication: none to thick
Cold rice texture	The texture of rice perceived after thirty min: soft to hard
Overall sensory evaluation (OSE)	Comprehensive evaluation of the rice

form. Cooked WGBR samples were presented to the candidates and the sensory evaluation data were collected, with the outliers removed. The details of the procedure followed the Group Standard—Method for sensory evaluation of whole-grain black rice for cooking and eating quality (T/HBLS 0015–2023), issued by the Hubei Province Association of Grain Sector, China, which was proposed by our team. When we first started this work, there was no available information regarding the taste of reference black rice. After tasting a large number of black rice samples, the panelists reached a consensus such that Huamoxiang (HMX), a variety recently released as cooking and steaming type of whole grain rice (Zhang et al. 2024), was selected a reference for good taste, and Heixiangmi (HXM) as a reference for poor taste. We mixed the two varieties with a weight ratio 1:1 to get a moderate taste as a control for scoring in the sensory tests.

In this work, each sample was evaluated by 10 to 15 trained panelists, consisting of staff and graduate students from Huazhong Agricultural University, aged 23- to 45-years. The cooked black rice was assessed for 11 characters including aroma, appearance (color, glossiness, and grain integrity), texture properties (stickiness, springiness, hardness, and mouth/throat coating), flavor, cold rice texture and overall sensory evaluation (OSE) where OSE was used as the overall sensory score for the sample (Table S1). The strength for each of the 11 characters was evaluated a using a 7-point intensity scale ranging from “none” to “strong” (0 = none, 1 = slight amount, 2 = moderate amount, 3 = strong amount) with two opposite directions (plus and minus) shown in Table S1. The reference sample was made of two different black rice varieties HMX bred by Huazhong Agricultural University (Zhang et al. 2024) and HXM obtained from the market mixed with a weight ratio 1:1. The reference sample was marked as “0”, and each sample was evaluated by comparing to the reference to give an intensity score. HMX is accepted as good taste (+3) and HXM as poor taste value (−3) by the panelists, which also affirmed the mixed sample of HMX:HXM (1:1) as reference.

A total of 78 sensory tests were carried out including: 16 tests conducted in November 2021 for samples harvested from Lingshui, and 62 tests conducted from April to June 2022 for samples harvested from Wuhan. The sensory tests were done once or twice per day, at 10:00 am and 2:30 pm. Each test included 9 samples with one reference and one blind control (HMX). The mean values of the OSE were calculated from the scores provided by valid evaluators, while the abnormal sensory data was eliminated through outlier tests. The intensity score was converted to percentage score by the formula $T = 75 + ((100–75)/3 \times A)$, in which T is the percentage score, and A is the intensity score. The reference sample was scored 75 by the percentage score.

Measuring the taste value using Rice Taste Evaluation System

Rice Taste Evaluation System (Satake Corp., Hiroshima, Japan) is a device that calculates rice taste values to mimic human sensory evaluation (Mikami 2009). This device has been widely used in quantifying taste value of milled white rice (Yang et al. 2013; Hori et al. 2016; Zhang et al. 2016; Iijima et al. 2019; Chen et al. 2021; Hori et al. 2021; Shi et al. 2022; Xiong et al 2022; Yuan et al. 2022; Yao et al. 2023), which has greatly facilitated eating quality studies. To explore the feasibility of using this device in taste evaluation of WGBR, we employed two units of the Rice Taste Evaluation System (STA1B-RHS1A) in the analysis, a cooked rice analyzer (STA1B-CN) and hardness and stickiness meter (RHS1A-CN).

Following the manufacturer's instruction, samples of cooked rice (7 g) were weighed and placed in stainless steel cups and pressed into a rice cake using a cooked rice press. The cups were placed in an air-cooling apparatus for 20 min, and then cooled at room temperature for 2 h before testing. The cooked black rice taste characteristics were evaluated using Rice Taste Evaluation System.

For optical characteristics, the device (STA1B-CN) was preheated for 30 min, and calibration was performed using a black and white reference plate. The rice sample as cake (7 g) was placed in a stainless-steel sample ring (diameter = 30 mm, height = 9 mm). Each side of sample was evaluated once. Three measurements were obtained per sample for four optical parameters, reflected light (R1, R2) and transmitted light (T1, T2) values. The textural parameters were evaluated with hardness and stickiness meter (RHS1A-CN) to collect four textural parameters, hardness, stickiness, balance and elasticity (Mikami 2009). The preformed black cooked rice cake of the same sample was analyzed to determining the textural properties with texture profile analysis (TPA) method. Test of each sample was repeated three times, and mean values were calculated.

Data processing and statistical analysis

Python Language v. 3.9.0 (Python/3.9.0) and R Language v. 4.2.0 (R/4.2.0) were used for data processing. The R package corrplot v0.92 was utilized to conduct correlation analysis between the OSE scores and 10 variables using the default Spearman correlation coefficient. Significant differences were deemed to occur at $P<0.05$, $P<0.01$ and $P<0.001$. The regression analysis was conducted using R function lm. Outliers are detected using the outlierTest function in the R package car v. 3.0.12. Machine learning modeling was performed using the Python library PyCaret v. 3.3 (pycaret.org. PyCaret, April 2024. URL https://pycaret.org/. PyCaret version 3.3) with default parameters.

Results

Sensory evaluation and the taste score distribution of the WGBR samples

We evaluated the quality and repeatability of the sensory evaluation data as follows. Totally 247 of 317 accessions harvested from the Wuhan 2021 field planting had two replications, of which 87 accessions also had harvests from Lingshui 2020 planting. We investigated the repeatability of overall sensory evaluation (OSE) values by calculating correlation between OSE scores of the two repeats from the Wuhan field planting, the high coefficient ($R^2=0.939$, $P=1.610\times10^{-150}$) indicated almost perfect repeatability (Fig. 1A). The 87 samples planted in two different seasons and locations also showed very high correlation ($R^2=0.933$, $P=1.387\times10^{-51}$) (Fig. 1B). This result clearly indicates that sensory evaluation using the panelists is a reliable approach for rice sensory study.

Because the very different environmental conditions, the 133 accessions planted in Lingshui and 317 accessions in Wuhan were treated as 450 independent entries in the analysis. The OSE scores given by the panelists (Fig. 2) showed that 22 of the 450 entries had OSE values above 90 representing the highest taste scores, and 148 entries with scores 80–89 indicating intermediate taste. The remaining entries

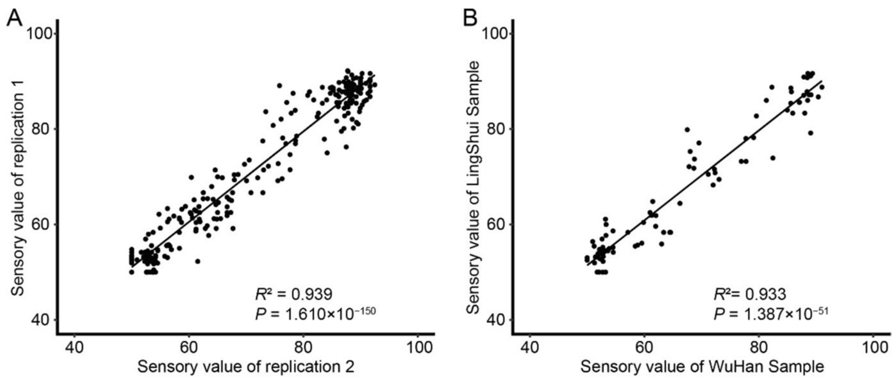

Fig. 1 Repeatability of sensory evaluation for black rice in different planting seasons and locations. **A** 247 accessions with two replications planted in Wuhan 2021; **B** 87 accessions planted in both Lingshui 2020 and Wuhan 2021

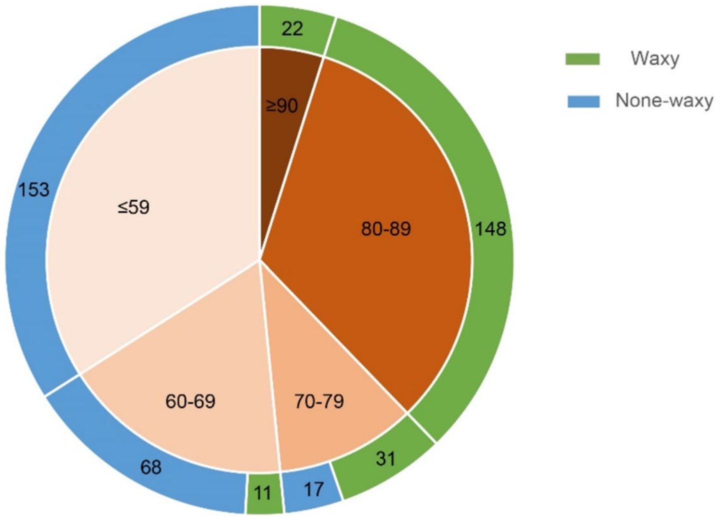

Fig. 2 Distribution of the sensory score classified by waxy endosperms for 450 black rice samples

received lower taste scores including 48 samples with score 70–79, 79 entries scoring 60–69, and 153 entries below 59.

We checked the endosperm of the rice grain and found that all the entries receiving OSE scores above 80 had glutinous endosperm (waxy) and all the entries scoring below 59 are of non-waxy endosperm, while those receiving scores of 60–79 have both waxy (42) and non-waxy (85) endosperms (Fig. 2).

Correlations between the OSE and the other ten characters of sensory evaluation

In addition to OSE score, the sensory evaluation provided data for another 10 characters: aroma, color, glossiness, grain integrity, stickiness, springiness, hardness, mouth/throat coating, flavor, cold rice texture. Totally the sensory evaluation data from 775 samples were analyzed, including 133 accessions with one replication each planted in Lingshui, 247 accessions each with two replications and 70 accessions each with one replication planted in Wuhan, together with the 78 data points (from 78 tests) of HMX used as blind control in each test. Each sample was assessed by 10–15 panelists, producing 9099 tasting scores. Table 2 shows the correlations between the OSE score and the 10 characters. The OSE score was highly positively correlated with the cold rice texture ($r=0.956$, $P<5\times10^{-324}$), mouth/throat coating ($r=0.939$, $P<5\times10^{-324}$), stickiness ($r=0.926$, $P<5\times10^{-324}$), flavor ($r=0.904$, $P<5\times10^{-324}$), springiness ($r=0.887$, $P<5\times10^{-324}$), and glossiness ($r=0.877$, $P<5\times10^{-324}$). It was also positively correlated with color ($r=0.478$, $P<5\times10^{-324}$) and aroma ($r=0.292$, $P=7.98\times10^{-225}$). In contrast, OSE was highly negatively correlated with hardness ($r=-0.871$, $P<5\times10^{-324}$). Little correlation was detected between OSE and grain integrity ($r=0.025$, $P=0.013$).

Table 2 Correlation coefficients (r) between sensory evaluation attributes ($n = 9099$)

	Aroma	Color	Glossiness	Grain integrity	Stickiness	Hardness	Springiness	Mouth/throat coating	Flavor	Cold rice texture	Overall sensory evaluation
Aroma		0.175 ***	0.276 ***	0.088 ***	0.267 ***	−0.185 ***	0.257 ***	0.253 ***	0.316 ***	0.259 ***	0.292 ***
Color			0.495 ***	0.005 ***	0.429 ***	−0.393 ***	0.424 ***	0.451 ***	0.417 ***	0.458 ***	0.478 ***
Glossiness				−0.008	0.879 ***	−0.806 ***	0.797 ***	0.851 ***	0.776 ***	0.882 ***	0.877 ***
Grain integrity				1	0.013	0.038 **	0.052 ***	0.024 *	0.066 ***	0.013	0.025 *
Stickiness						−0.869 ***	0.853 ***	0.905 ***	0.836 ***	0.921 ***	0.926 ***
Hardness							−0.787 ***	−0.873 ***	−0.784 ***	−0.872 ***	−0.871 ***
Springiness								0.857 ***	0.842 ***	0.863 ***	0.887 ***
Mouth/throat coating									0.865 ***	0.936 ***	0.939 ***
Flavor										0.865 ***	0.904 ***
Cold rice texture											0.956 ***

A t-test was used to assess the significance of differences.

*** significant at $P < 0.001$; ** significant at $P < 0.01$; * significant at $P < 0.05$

Correlations between OSE scores and RTES parameters

Rice Taste Evaluation System (RTES) produced data of 8 characteristic parameters for each WGBR sample: reflected light R1, reflected light R2, transmitted light T1, transmitted light T2, hardness, stickiness, balance and elasticity. R1 is a reflection wavelength of 540 nm, which is used to determine the appearance of rice. R2, reflecting wavelength of 970 nm, is used to measure the gelatinization degree of rice. T1, with a transmission wavelength of 540 nm, is to assess the degree of rehardening of cooked rice. T2 has a transmission wavelength of 640 nm used to monitor the yellowing degree of rice. Balance is the ratio of stickiness to hardness (Mikami 2009).

To investigate how these machine parameters are related to the sensory evaluation of cooked WGBR, we calculated correlations between OSE scores by panelists and the measurements of the RTES parameters. Figure 3 shows that the OSE scores had the highest correlation with balance ($r=0.869$, $P=6.546\times10^{-238}$), followed by transmitted light T2 ($r=0.760$, $P=1.316\times10^{-146}$); and was highly negatively correlated with hardness ($r=-0.844$, $P=3.443\times10^{-210}$), reflected light R2 ($r=-0.796$, $P=6.614\times10^{-171}$) and reflected light R1 ($r=-0.688$, $P=6.074\times10^{-105}$). OSE scores were also highly significantly correlated with stickiness ($r=0.577$, $P=1.662\times10^{-69}$), elasticity ($r=0.566$, $P=3.326\times10^{-66}$), transmitted light T1 ($r=0.563$, $P=9.576\times10^{-64}$). These correlations suggest that data produced by RTES are informative for sensory analysis of WGBR.

A multiple linear regression equation for predicting sensory score based on 8 parameters from RTES

To explore the usefulness of the RTES to predict taste score for future WGBR samples, we performed a multiple linear regression (MLR) analysis using OSE score as the dependent variable and the machine parameters as independent variables. In doing so, 620 samples were picked up randomly as the calibration set for

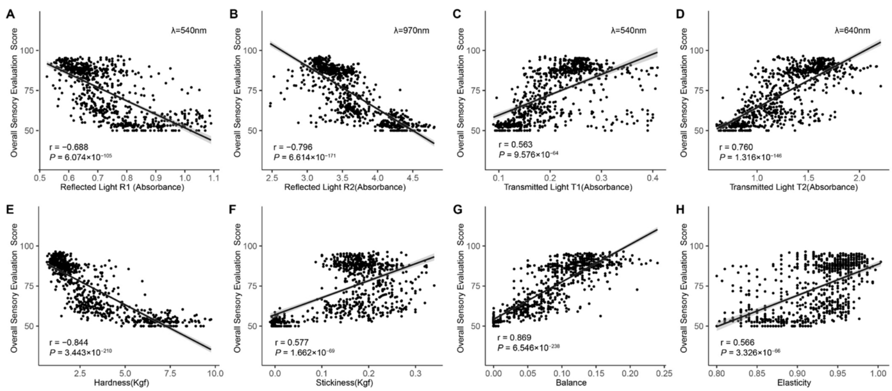

Fig. 3 The correlations between the sensory value and eight parameters of rice taste analyzer

constructing the regression equation, and 155 samples were reserved as the validation set for prediction. The following MLR equation was obtained:

$$Y = 123.999 - 4.836 \times A_{(R1)} - 8.427 \times A_{(R2)} - 8.841 \times A_{(T1)} + 11.986 \times A_{(T2)} - 1.838 \times V_{(Hardness)} - 19.314 \times V_{(Stickness)} + 103.048 \times V_{(Balance)} - 31.482 \times V_{(Elasticity)}$$

Y: the predicted taste value of the sample, $A_{(R1)}$- $A_{(R4)}$: the absorbance of 4 wavelength of a cooked rice analyzer (STA1B-CN), $V_{(Hardness)}$- $V_{(Elasticity)}$: the output of the hardness and stickiness meter (RHS1A-CN).

The partial regression coefficients of all the variables R1, R2, T1, T2, hardness, stickiness, balance, elasticity are significant at 0.05 (Table S2). This equation produced an R^2 0.867 with an F-value of 499.4, $P < 2.2 \times 10^{-16}$ (Table S3).

We validated the performance of the MLR equation using the 155 samples that were reserved as the validation set. In doing so, the observed values for each of the variables were plugged in the equation to calculate the predicted values. The resulting coefficient of determination (R^2) was 0.826 between the predicted values and OSE scores, with residual mean square error (RMSE) 6.074 (Fig. 4A). This result clearly indicates that this equation can well catch the variation of the machine characteristic contributing to eating quality of cooked WGBR, suggesting that the RTES can be a useful tool for sensory test of cooked WGBR.

Predicting sensory value using machine learning methods

Machine learning, which focuses on the use of data and algorithms to imitate the way that humans learn, can make useful prediction or generate content from data. On the basis of large-scale data, machine learning can better improve the prediction effect of the model (Greener et al. 2022). PyCaret is currently a widely used machine learning library, composed of a large package of many data libraries like scikit-learn, XGBoost, LightGBM, CatBoost, Optuna, Hyperopt, and Ray (pycaret.org. PyCaret, April 2024). It allows models to be evaluated, compared, and tuned on a given dataset with just a few lines of code.

In this study, 620 samples were picked up randomly for training set, and remaining 155 samples were reserved as the testing set. Nineteen statistical models in PyCaret were employed to predict the sensory values for cooked WGBR. Each model was evaluated in a tenfold cross-validation and each fold was assessed by the correlation between OSE and predicted values. The metrics were calculated to select the optimal prediction model based on Mean Absolute Error (MAE), Mean Square Error (MSE), Root Mean Square Error (RMSE), coefficient of determination (R^2), Root Mean Square Log Error (RMSLE) and Mean Absolute Percentage Error (MAPE) (Table S4). It was found that the CatBoost Regressor (CBR) model provides the best prediction results ($R^2 = 0.922$). In this model, the contributions of hardness and balance to sensory value were 21.93% and 19.11% respectively, followed by R2 (18.30%), T2 (12.97%), elasticity (9.75%), these five parameters contribute 82.06% of the overall sensory score (Fig. S2). When the tasting values of

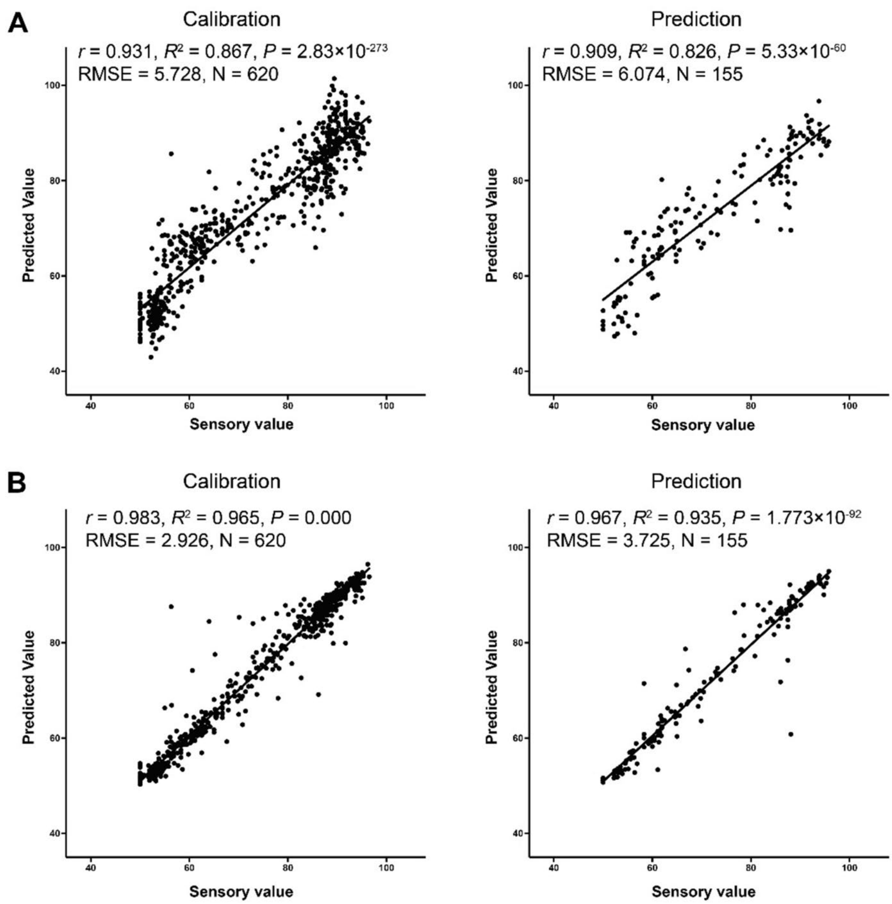

Fig. 4 Scattergrams of calibration and prediction of two models for sensory value of WGBR. **A**: Calibration and prediction of MLR model; **B**: Calibration and prediction of CBR model

testing set of 155 samples were predicted by the CBR model, the coefficient of determination (R^2) was 0.935 (Fig. 4B).

The application of the MLR model and CBR model for commercial black rice samples

In order to further verify the accuracy of the prediction of the MLR model and CBR model, we tested 23 black rice samples including 22 commercial black rice samples of different brands and from different origin were purchased from Taobao, with HMX as the reference. Sensory evaluation was carried out to obtain the OSE score, and the 8 characteristic parameters were measured by Rice Taste Evaluation System. The results showed that the taste values of black rice samples purchased in the market were generally low, ranging from 60 to 70 points (Table S5). A strong

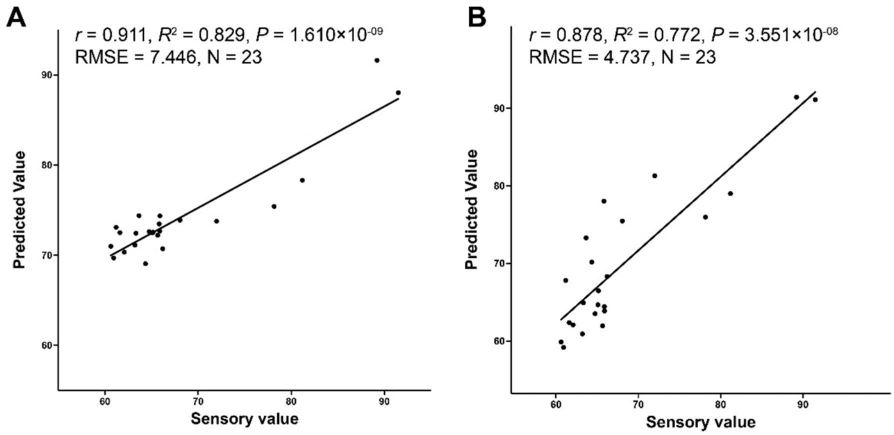

Fig. 5 Sensory prediction for commercial black rice from the market using MLR model (**A**) and CBR model (**B**)

linear relationship was found between the predicted taste value obtained by the MLR model and the OSE of the sensory evaluation ($R^2=0.829$, $P=1.610\times10^{-09}$) (Fig. 5A). There was also a strong linear relationship between the predicted value and the OSE ($R^2=0.772$, $P=3.551\times10^{-08}$) based on CBR model from machine learning (Fig. 5B). Compared to CBR model, the predicted value from MLR is closer to the OSE by panelists. It seems to suggest that the CBR model obtained from machine learning may produce better outcome than MLR with large datasets in the case of calibration (N = 620) and validation (N = 155) sets in this study. However, its performance for taste score prediction is less robustness in small dataset (N = 23). Nonetheless this approach may still need further attention.

Discussion

The Rice Taste Evaluation System evaluation equipment is designed to evaluate the cooking and eating properties of cooked rice, all 8 parameters are selected based on well milled white rice. The reflected wavelength 540 nm (R1) observes the appearance of rice; when the whiteness increases, the glossiness decreases, and the sensor output increases. Reflected wavelength 970 nm (R2) measures the gelatinization degree of cooked rice. While the transmitted wavelength 540 nm (T1) gauges the degree of rehardening of cooked rice, transmitted wavelength 640 nm (T2) assesses the yellowing degree of rice (Lai et al. 2011).

Our results show that the OSE score of WGBR has the highest correlation with balance ($r=0.869$), followed by transmitted light T2 ($r=0.760$), stickiness ($r=0.577$), elasticity ($r=0.566$), transmitted light T1 ($r=0.563$); and was highly negatively correlated with hardness ($r=-0.844$), reflected light R2 ($r=-0.796$) and reflected light R1 ($r=-0.688$). The CBR model stresses on the importance of the correlations of hardness, balance and R2 with sensory value (21.93%, 19.11% and 18.30%, respectively), followed by T2 (12.97%), elasticity (9.75%), R1 (7.98%), stickiness (5.85%) and T1 (4.11%). The former five parameters can make a total of 82.06% contribution to the overall sensory score. It seems that the transmitted wavelength 540 nm (T1) may not be very relevant in the sensory evaluation of WGBR.

It may be interesting in this connection to compare the predictivity of our model with results from similar studies of milled white rice. However, most studies only used the Rice Taste Evaluation System as a tool based on the manufacturer's default setting to obtain taste measurements for the rice samples. In other cases, the parameters used in the analyses or the sample sizes included in the studies are not directly comparable. It may also be interesting to compare the weights on these parameters (regression coefficients) in the multiple regression equation obtained in our study to the default setting of Rice Taste Evaluation System by the manufacturer for milled white rice. Regrettably such information is not available yet at the present.

An important finding from this work is that samples of WGBR with high taste score (≥ 90) are exclusively ones with waxy endosperm, while none of those with very low taste score have waxy endosperm. This suggests that very low (or zero) amylose content is a necessary condition for palatability of the whole grain rice. However, only a small proportion of the accessions with waxy endosperm had high taste scores suggesting that the sensory quality of whole grain rice is more complex than waxy endosperm.

For genetic improvement of sensory values of WGBR, future studies need be directed to identifying the material and chemical basis of the taste, including the involved substances and their chemical property, and the relationship of the WGBR taste with the traditional characters of cooking and eating quality of milled white rice. For genetic improvement of cooking and eating quality, research should also be undertaken to address the genetic basis, and hence to identify the genes for eating and cooking quality of WGBR.

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Author contributions Hangxue Tian performed the experiments, analyzed data. Yanhua Li participated in the experiments and analyzed data. Yunrui Lu prepared the figures and tables. Qinglu Zhang, Zhengji Wang, Shanshan Li, Yuqiong Zhou participated in the experiments. Qifa Zhang revised and edited the manuscript. Jinghua Xiao designed the experiment, wrote the original draft and editing.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The experiments comply with the ethical standards in the country in which they were performed. The Tab of Experimental Ethical, Huazhong Agricultural University (ID Number: HZAUHU-2021–0033).

Conflict of interest The authors declare that they have no conflict of interest.

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