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Higher yield and grain quality adaptability of newly developed japonica rice cultivars under recent climatic variability in Central Korea: Evaluation with a quality climate adaptability index

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Abstract. This study introduces and evaluates a Quality Climate Adaptability Index (QCAI) that integrates head rice ratio, protein content and palatability value to complement yield-centred assessment of rice cultivar adaptability under climatic variability. Five japonica rice cultivars – Chucheong, Daean, Samkwang, Chilbo and Chamdream – were evaluated under uniform cultivation conditions in Hwaseong, central Korea, from 2020 to 2025. The study period included contrasting grain-filling environments, particularly high temperature in 2024 and high precipitation with low solar radiation in 2025, allowing comparison of grain-quality responses across contrasting climatic conditions. In 2024, head rice ratio showed the most pronounced adverse response among the QCAI components, whereas no consistent deterioration of the three component traits was observed in 2025. Newly developed cultivars produced a higher mean milled rice yield than conventional cultivars (5.42 vs. 4.91 t ha^{-1}), and Chamdream and Samkwang ranked highest in yield-based climate adaptability. The annual group mean QCAI of newly developed cultivars was significantly higher than that of conventional cultivars ($P = 0.0023$). The two highest mean QCAI values were observed for Samkwang (0.65) and Chamdream (0.63), with no significant difference between them ($P = 0.949$); Chilbo was intermediate (0.01), whereas Chucheong (−0.60) and Daean (−0.69) were lower. These results indicate that QCAI complements yield-based assessment by integrating three representative grain-quality traits – head rice ratio, protein content and palatability value – into a measure of relative grain-quality performance under interannual climatic variability, while the stability of individual quality traits should be evaluated separately using extended multi-year data.

Key words: climate adaptability, grain quality, head rice ratio, *Oryza sativa* L., palatability value, protein content.

INTRODUCTION

Recent climate change has increased mean and minimum temperatures during the rice-growing season. Extreme heat and extreme precipitation events are also likely to become more frequent in major rice-producing regions worldwide (Zhao et al., 2022). In Korea, rising temperatures and abnormal weather events affect rice growth, yield and grain quality stability, which highlights the need to consider both cultivar adaptability and improved cultivation practices (Seo et al., 2020). In particular, higher night-time minimum temperatures closely relate to reductions in rice yield (Peng et al., 2004; Riaz et al., 2024), and high temperatures during grain filling act as major meteorological stresses that adversely affect rice growth, yield components and yield stability (Horie, 2019; Kumar et al., 2021; Hossain et al., 2024). In central Korea, recent meteorological conditions during the rice-growing season have also shown a warming trend compared with the normal climate, with high temperatures and concentrated rainfall occurring at specific growth stages. In particular, abnormally high temperature combined with high precipitation and low solar radiation during grain filling may create unfavourable conditions for cultivation stability and grain quality maintenance.

These abnormal weather conditions not only reduce rice growth and yield performance but also strongly influence grain appearance quality, protein content and eating quality. High temperature promotes chalky grain formation during grain filling and thereby reduces grain translucency and appearance quality (Nevame et al., 2018). Yamakawa et al. (2007) showed that high temperature during grain filling suppresses the expression of starch synthesis-related genes and increases the expression of starch degradation- and heat-shock-response-related genes, thereby causing abnormal starch accumulation and chalkiness formation. High temperature during grain filling also increases the occurrence of chalky, immature and cracked grains, deteriorates appearance quality, and induces physicochemical changes such as reduced amylose content and increased protein content (Morita et al., 2016; Horie, 2019; Shiotsu et al., 2021). Yang et al. (2023) further showed in a field-warming experiment that increased temperature affects not only rice yield but also milling quality, appearance quality and eating-quality-related traits, and that cultivars differ in these responses. However, conventional evaluations of cultivar adaptability still focus mainly on yield and yield stability, and such yield-centred approaches do not adequately capture differences in grain quality stability under climate change conditions.

In addition, successful cultivar dissemination depends not only on yield performance but also on quality traits such as milling recovery, head rice ratio, protein content and eating quality. Protein content, amylose content and RVA pasting properties strongly influence rice eating quality, and protein content in particular serves as a major physicochemical indicator explaining variation in palatability value (Shi et al., 2022). Sreenivasulu et al. (2015) argued that breeders should consider quality stability, including head rice yield, milling quality and chalkiness occurrence, alongside yield performance when developing climate-resilient rice cultivars under high-temperature stress. Therefore, the evaluation of rice cultivars under climate change requires a complementary approach that considers grain quality together with yield performance. Evaluating QCAI is important because it integrates major quality traits affected by

climatic variability into a single standardised index, allowing comparison of cultivars that maintain relatively favourable overall grain quality across years. In particular, for table rice cultivars, even high and stable yield may not ensure acceptance by rice processors and consumers if appearance quality or eating quality deteriorates. Thus, QCAI provides complementary information on grain quality that is not captured by yield-based climate adaptability assessment alone.

This study aimed to develop and evaluate a Quality Climate Adaptability Index (QCAI) that integrates head rice ratio, protein content and palatability value to assess the relative overall grain quality of rice cultivars under interannual climatic variability. Using five japonica rice cultivars repeatedly grown under identical paddy field and cultivation conditions in Hwaseong, Gyeonggi-do, Korea, from 2020 to 2025, this study compared conventional and newly developed cultivars in terms of yield performance, grain quality and climate adaptability. By applying QCAI together with a yield-based climate adaptability index, this study sought to evaluate cultivar adaptability from both productivity and grain quality perspectives under recent climatic variability.

MATERIALS AND METHODS

Experimental materials and cultivation conditions

The experiment took place in a paddy field at Gyeonggi-do Agricultural Research and Extension Services in Hwaseong, Gyeonggi-do, Korea (37.2196°N, 127.0437°E). Five japonica rice cultivars – Chucheong, Daean, Samkwang, Chilbo and Chamdream – were used. In the central region of Korea, particularly in Gyeonggi-do, the cultivation system for japonica rice cultivars used for table rice has long relied on introduced Japanese cultivars and domestically bred cultivars. Chucheong is an introduced cultivar derived from the Japanese cultivar 'Akibare', which entered Korea in 1970 and has long served as a major medium-late maturing cultivar in Gyeonggi-do. Daean is a domestic medium-late maturing cultivar bred in 1995 and has been widely grown mainly in northern Gyeonggi-do. This study classified Chucheong and Daean, which have been cultivated for many years in the central region of Korea, as conventional cultivars.

The newly developed cultivar group consisted of Samkwang, Chilbo and Chamdream, all bred domestically after 2000. Samkwang is a medium-late maturing, multi-disease-resistant and high-quality japonica rice cultivar bred by the National Institute of Crop Science in 2003 and shows high adaptability to the central plain and mid-southern mountainous areas (Kim et al., 2007). Chilbo is a medium-late maturing, high-quality cultivar bred in 2007, characterised by a high head rice ratio, high milling recovery and good eating quality (Kim et al., 2009). Chamdream is a medium-late maturing, high-quality cultivar bred by Gyeonggi-do Agricultural Research and Extension Services in 2014 for adaptation to Gyeonggi-do, with low protein content and good eating quality (Jang et al., 2019). The reference yields and major grain-quality characteristics of the five cultivars are summarised in Table 1.

The study compared yield performance, grain quality traits and climate adaptability indices between the conventional and newly developed cultivar groups.

Table 1. Reference yield and grain-quality characteristics of the japonica rice cultivars used in this study

Cultivar	Cultivar group (release year)	Reference yield* (kg 10a^{-1})	Protein content (%)	Amylose content (%)	Milling recovery (%)	Head rice ratio (%)
Chucheong	Conventional (1970)	454	6.5	19.5	77.2	94.7
Daean	Conventional (1995)	511	6.6	19.1	76.6	94.8
Samkwang	Newly developed (2003)	569	5.7	18.3	76.5	94.5
Chilbo	Newly developed (2007)	557	6.4	18.3	78.5	92.5
Chamdream	Newly developed (2014)	559	5.4	19.5	76.8	88.8

* Reference yield represents the cultivar-specific baseline yield used for calculation of the yield-based climate adaptability index. Grain-quality values are background reference characteristics obtained from cultivar development reports or previous cultivar evaluations. Because these values were obtained in different years and experimental environments, they are provided to describe the characteristics of the experimental materials and were not used for statistical comparison in the present study.

The experimental period covered six years, from 2020 to 2025. All cultivars were grown under identical cultivation conditions throughout the experimental period. Seeds were sown on 20 April each year, and medium-aged seedlings were machine-transplanted on 20 May. The seeding rate was 120 g per nursery box (60×30 cm), and seedlings were transplanted at a spacing of 30×14 cm, corresponding to 238,100 hills ha^{-1}. Fertiliser was applied at 90–45–57 kg ha^{-1} as N–P_2O_5–K_2O. Each cultivar was grown in a single plot, and three replicate samples were collected within each plot for the measurement of major traits (Table 2).

Table 2. Experimental site and cultivation practices during 2020–2025

Experimental site	Sowing date (month.day)	Seed amount per nursery box (g)	Transplanting date (month.day)	Planting distance (row × hill, cm)	Fertiliser application rate (kg ha^{-1})
GARES*, Hwaseong	4.20	120	5.20	30×14	90-45-57 (N-P_2O_5-K_2O)

* Gyeonggi-do Agricultural Research and Extension Services.

Meteorological data

The study analysed meteorological data for the rice-growing period from 21 April to 20 October each year during the experimental period (2020–2025). Mean, maximum and minimum temperatures, sunshine duration, precipitation and solar radiation at or near the experimental site were examined. Meteorological data were obtained from nearby observation records provided by the Gyeonggi-do agricultural weather and pest system and from the Open MET Data Portal of the Korea Meteorological Administration. The analysis treated 20-year mean values for 2000–2019 at the experimental site as the normal climate and compared recent six-year means with this baseline.

Traits investigated

The study evaluated heading date, culm length and panicle length as growth-related traits. Number of panicles per hill, number of spikelets per panicle, ripened grain ratio, 1,000-brown-rice weight, milling recovery and milled rice yield were evaluated as yield-related traits. The number of panicles per hill was measured from 20 hills per plot,

and the number of spikelets per panicle was measured from five hills per plot. The ripened grain ratio was determined from five hills per plot after threshing, using water selection with a specific gravity of 1.0. The 1,000-brown-rice weight was calculated as the mean of three measurements, and the milled rice yield was determined from a harvested area of 6 m².

As grain quality traits, the study evaluated brown rice recovery, head rice ratio, protein content and palatability value. Rice samples used for grain quality analysis were milled to a milling yield of 90.4% of the brown-rice weight. Head rice ratio was determined using a grain image analyser (RGQI100B-KR, Satake Corporation, Higashihiroshima, Japan). Approximately 200 g of polished rice was thoroughly mixed, and one dedicated sample scoop (approximately 1,100 kernels) was introduced into the analyser. The instrument automatically classified approximately 1,000 kernels according to grain appearance, including whole, chalky, broken and damaged grains, and the head rice ratio was obtained from the instrument output.

Protein and amylose contents were measured in intact polished rice by near-infrared transmittance using a grain analyser (Infratec 1241, FOSS, Hillerød, Denmark). Approximately 200 g of polished rice was screened using a 600-μm standard test sieve to remove fine particles and was analysed without grinding or other pretreatment using the instrument calibration developed for rice.

Palatability value was measured using a cooked rice taste analyser (STA1B, Satake Corporation, Higashihiroshima, Japan). For each measurement, 30 g of polished rice was washed under running water for 30 s, water equivalent to 1.35 times the rice weight (40.5 g) was added, and the sample was soaked for 30 min. The rice was cooked for 35 min, allowed to stand for 10 min, gently mixed, and cooled for 20 min to approximately 25 °C. An 8-g portion of cooked rice was placed in the sampling ring, compressed for 10 s on each side, and measured on both surfaces. The instrument-derived palatability score, expressed on a 0–100 scale, was used for analysis. All grain quality measurements were performed in triplicate for each cultivar in each year, and the mean of the three measurements was used for subsequent analyses.

Yield-based climate adaptability index

The yield-based climate adaptability index used in this study was established based on the 'rate of adaptive-nonadaptive production change' indicator reported by the Rural Development Administration (2021). Accordingly, cultivar-specific milled rice yield data obtained from six years of repeated cultivation under identical field and cultivation conditions were used to reflect both mean yield and year-to-year variability. The yield-based climate adaptability index was calculated as 'yield index relative to reference yield + yield weighting – yield deviation index', as follows.

$$YCAI_i = \frac{\overline{Y_i}}{Yo_i} + \frac{\overline{Y}_i - 540}{100} - \frac{SDi}{200} \quad (1)$$

where $YCAI_i$ is the yield-based climate adaptability index for cultivar i; $\overline{Y}_i$ is the mean milled rice yield of cultivar i during 2020–2025; Yo_i is the cultivar-specific reference yield used for the index calculation; and SDi is the standard deviation of annual milled rice yield during 2020–2025. All yield values used in the equation are expressed in kg $10a^{-1}$.

The yield index relative to reference yield was calculated by dividing the observed yield by the reference yield; the observed yield was defined as the mean milled rice yield of each cultivar during the experimental period. Although yield values are presented as t ha^{-1} in the text and tables, the yield-based climate adaptability index was calculated using the original yield data expressed in kg $10a^{-1}$ to maintain consistency with the indicator reported by the Rural Development Administration (2021). The yield weighting was calculated by subtracting 540 kg $10a^{-1}$, the mean yield performance of table rice cultivars developed since the late 1990s, from the observed yield and dividing the difference by 100. The yield deviation index was calculated by dividing the standard deviation of cultivar-specific milled rice yield during the experimental period by 200; thus, greater year-to-year yield variability reduced the final index value. Therefore, this index was designed to have higher values for cultivars with higher mean yield and lower year-to-year variability.

Quality Climate Adaptability Index (QCAI)

Head rice ratio, protein content and palatability value were selected as component traits of QCAI because they represent appearance quality, physicochemical quality and eating quality, respectively, which are major components of marketable and consumer-oriented rice quality. Rice quality comprises multiple traits, including milling quality, appearance quality and eating quality; therefore, an integrated evaluation incorporating these traits is required because cultivar-specific quality characteristics cannot be fully evaluated using a single indicator (Tian et al., 2025). Based on this concept, this study calculated the Quality Climate Adaptability Index (QCAI) by integrating head rice ratio, protein content and palatability value.

For each quality trait, the mean value of three replicated measurements for each cultivar and year was first calculated, and then standardised as a Z-score using the mean and standard deviation of the five cultivars within the same year. The Z-score was calculated as follows.

$$Z_{ij} = \frac{x_{ij} - \overline{x}_j}{s_j} \quad (2)$$

where Z_{ij} – standardised value of a trait for cultivar i in year j; x_{ij} – trait value of cultivar i in year j; $\overline{x}_j$ – mean trait value of five cultivars in year j; s_j – standard deviation of trait values among five cultivars in year j.

QCAI was calculated by reflecting the direction in which each quality trait contributes to high grain quality, as follows.

$$\mathrm{QCAI} = \frac{\mathrm{Z(HR)} - \mathrm{Z(PC)} + \mathrm{Z(PV)}}{3} \quad (3)$$

where HR – head rice ratio; PC – protein content; PV – palatability value; Z – standardised value of each trait within a year.

Head rice ratio and palatability value were incorporated in the positive direction because higher values indicate better grain quality, whereas protein content was incorporated in the negative direction because lower protein content is favourable for eating quality. This year-wise standardisation was applied to reduce the effects of annual meteorological variation on the absolute values of quality traits and to compare the relative quality level of cultivars within the same year.

Because the year-wise Z-score standardisation centres each component trait around the mean of the five cultivars, a QCAI value of zero represents the mean relative grain-quality level of the tested cultivar set within a given year; positive and negative values indicate above- and below-average relative quality performance, respectively. Because an independent external benchmark for QCAI was not available in the present study, QCAI was evaluated as a relative composite index rather than as a predictive model. Chucheong and Daean were classified as conventional cultivars and compared with the newly developed cultivars at the group level.

Interannual stability of head rice ratio, protein content and palatability value was evaluated for each cultivar using the coefficient of variation (CV), calculated as (standard deviation / mean) × 100 from the annual values for 2020–2025. A sensitivity analysis was conducted by recalculating mean QCAI values and cultivar ranks after excluding one year at a time from the six-year dataset.

To examine the relationships between climatic variability and crop responses, Pearson correlation coefficients were calculated using annual mean values from 2020 to 2025. Because the five cultivars were exposed to the same climatic conditions within each year, trait values were averaged across the five cultivars for each year, and each year was treated as one climatic observation ($n = 6$). Milled rice yield was correlated with mean temperature, precipitation and solar radiation during the entire rice-growing season (21 April–20 October), whereas head rice ratio, protein content and palatability value were correlated with the corresponding climatic variables during the grain-filling period (16 August–20 October). Because the correlation analysis was based on six annual observations, the results were interpreted with caution and used to describe general relationships between climatic factors and crop traits. The same cultivar-averaged values were also used for descriptive comparison of grain quality responses under the contrasting grain-filling conditions in 2024 and 2025.

The difference in QCAI between conventional and newly developed cultivar groups was tested by a paired *t*-test using annual group mean QCAI values from 2020 to 2025. Annual QCAI values of Samkwang and Chamdream were also compared by paired *t*-test because their six-year mean QCAI values were similar. Statistical significance was determined at $P < 0.05$. Statistical analyses were performed using Microsoft Excel.

RESULTS AND DISCUSSION

Climatic trends during the rice-growing seasons (2020–2025)

Analysis of the major meteorological variables during the rice-growing seasons from 2020 to 2025 showed that the six-year mean temperature was 22.3 °C, 0.8 °C higher than the normal climate value of 21.5 °C for 2000–2019. Maximum and minimum temperatures also increased by 0.3 °C and 1.0 °C, respectively. The greater increase in minimum temperature than in maximum temperature is noteworthy because high night-time temperature during the early grain-filling stage can increase chalkiness and reduce rice appearance quality (Long et al., 2023). The mean sunshine duration over the recent six years was 1,074.9 h, 96.2 h lower than the normal value. In contrast, precipitation reached 1,176.9 mm, which was 128.5 mm higher than normal, and solar radiation reached 3,138.9 MJ m^{-2}, 137.2 MJ m^{-2} higher than normal (Table 3). Together, these results indicate that recent rice-growing seasons at the experimental site were

generally warmer than the normal climate and showed substantial year-to-year variation in rainfall and solar radiation.

Comparison of meteorological factors during the grain-filling period (16 August–20 October) further highlighted this interannual variability (Table 3). In 2025, precipitation reached 593.1 mm and solar radiation declined to 850.8 MJ m^{-2}, producing the most pronounced high-precipitation and low-solar-radiation conditions among the six years; the mean temperature in that year was also high at 22.8 °C, second only to 2024.

Table 3. Climatic conditions during the rice-growing season and grain-filling period at Hwaseong, Gyeonggi-do, Korea, from 2020 to 2025, compared with the 2000–2019 normal climate

Period	Year	Mean temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Sunshine duration (h)	Precipitation (mm)	Solar radiation (MJ m^{-2})
Rice-growing season (21 Apr–20 Oct)	2020	21.6	27.9	16.8	1,202.3	1,426.3	3,057.3
	2021	22.6	28.4	17.9	841.6	796.4	3,063.7
	2022	22.3	28.4	17.4	904.0	1,536.2	3,226.1
	2023	21.9	26.7	17.8	1,173.4	1,127.6	3,132.1
	2024	22.8	27.7	18.6	1,261.4	1,093.5	3,306.6
	2025	22.5	27.1	18.5	1,066.8	1,081.3	3,047.7
	Mean (2020–2025)	22.3	27.7	17.8	1,074.9	1,176.9	3,138.9
	Normal (2000–2019)*	21.5	27.4	16.8	1,171.1	1,048.4	3,001.7
	Difference from normal**	+0.8	+0.3	+1.0	−96.2	+128.5	+137.2
Grain-filling period (16 Aug–20 Oct)	2020	21.2	27.7	16.3	456.0	306.5	1,018.8
	2021	21.7	27.0	17.5	224.8	382.5	854.7
	2022	20.6	26.8	15.8	288.0	398.7	1,008.8
	2023	21.5	26.2	17.5	392.4	246.2	959.4
	2024	23.3	27.9	19.5	410.8	355.4	982.8
	2025	22.8	26.8	19.6	284.7	593.1	850.8
	Mean (2020–2025)	21.9	27.1	17.7	342.8	380.4	945.9
	Normal (2000–2019)	20.6	26.6	15.8	409.6	293.5	914.8
	Difference from normal	+1.3	+0.5	+1.9	−66.8	+86.9	+31.1

* Normal climate refers to the 20-year average for 2000–2019. ** Difference from normal was calculated as the mean value for 2020–2025 minus the corresponding normal climate value for 2000–2019; positive and negative values indicate higher and lower values than normal, respectively.

In contrast, 2024 recorded the highest mean temperature (23.3 °C), indicating the most distinct abnormal high-temperature conditions relative to the normal climate. Precipitation during grain filling was also above normal in 2020, 2021, 2022 and 2024, whereas solar radiation remained above normal in 2020, 2022, 2023 and 2024. These patterns suggest that grain-filling environments varied greatly among recent years, with 2024 characterised primarily by high temperature and 2025 by combined high precipitation and low solar radiation.

The grain-quality responses to these contrasting conditions also differed. Across the five cultivars, mean head rice ratio decreased from 88.1% during 2020–2023 to 66.2% in 2024, while mean protein content increased from 5.3% to 5.6% and mean palatability value decreased from 81.1 to 76.2. Thus, head rice ratio showed the most pronounced adverse response among the three QCAI component traits under the high-temperature conditions of 2024. This pattern was also consistent with the correlation analysis, in which head rice ratio showed the strongest association with mean temperature during the grain-filling period ($r = -0.70$, $P = 0.118$; Table 6), although the relationship was not statistically significant.

In 2025, however, the corresponding means were 89.8%, 5.0% and 86.4, respectively, and no consistent deterioration was observed among the three QCAI component traits despite high precipitation and low solar radiation. Therefore, no single quality trait could be identified as particularly sensitive to the high-precipitation and low-solar-radiation conditions of 2025.

This interpretation agrees with previous studies showing that high temperature during grain filling disrupts starch accumulation, promotes chalkiness and reduces appearance quality, and that cultivars differ in their yield and quality responses to such stress (Yamakawa et al., 2007; Morita et al., 2016; Yang et al., 2023). Mitsui et al. (2016) also showed that high temperature during grain filling disrupts the balance between starch synthesis and degradation in the endosperm, inhibits dense starch granule accumulation, and thereby induces chalkiness and reduces head rice ratio.

Grain yield and yield components

Table 4 summarises the six-year mean yield and yield components of the tested cultivars. The newly developed cultivars generally showed higher yield performance than the conventional cultivars. In the conventional cultivar group, the mean number of panicles per hill was 18.2, spikelets per panicle 65.2, ripened grain ratio 89.5%, 1,000-grain brown rice weight 22.4 g, milling recovery 82.8% and milled rice yield 4.91 t ha^{-1}. The newly developed cultivar group had a similar mean number of panicles per hill (18.1), but produced more spikelets per panicle (78.9) and showed a slightly higher ripened grain ratio (90.8%). The mean 1,000-brown-rice weight (22.1 g) and milling recovery (82.9%) were similar between the two groups. However, the newly developed cultivar group achieved a higher mean milled rice yield of 5.42 t ha^{-1}, which exceeded that of the conventional group by 0.51 t ha^{-1}.

At the cultivar level, Chamdream produced the highest milled rice yield (5.66 t ha^{-1}), followed by Samkwang (5.58 t ha^{-1}), whereas Daean recorded the lowest yield (4.83 t ha^{-1}). These results suggest that the higher yield of the newly developed cultivar group resulted mainly from the increased number of spikelets per panicle rather than from differences in panicle number, ripened grain ratio or 1,000-grain weight. Samkwang and Chamdream therefore showed relatively high yield performance and appear to be better adapted to recent climatic conditions in the central region of Korea.

Grain quality traits and Quality Climate Adaptability Index (QCAI)

Table 5 presents the mean grain quality traits, their interannual variability, and QCAI values of the tested cultivars during 2020–2025. The newly developed cultivar group generally outperformed the conventional cultivar group in both grain quality traits

and quality-based climate adaptability. In the conventional group, the mean head rice ratio was 83.5%, protein content 5.6%, palatability value 79.0 and mean QCAI –0.65. In contrast, the newly developed group showed a higher mean head rice ratio (85.6%), lower protein content (5.1%) and higher palatability value (82.6), resulting in a positive mean QCAI of 0.43. A paired *t*-test using annual group mean QCAI values showed that the newly developed cultivar group had a significantly higher QCAI than the conventional group ($P = 0.0023$). This result indicates that the newly developed cultivars maintained better quality adaptability than the conventional cultivars under recent climatic conditions.

The sensitivity analysis excluding one year at a time showed that the overall cultivar ranking remained consistent. In all six recalculations, Samkwang and Chamdream remained the two highest-ranked cultivars, Chilbo remained third, and Chucheong and Daean remained the two lowest-ranked cultivars, although the order within the top two and bottom two varied in some cases. These results indicate that the overall QCAI ranking was not dependent on any single year. However, further validation using additional cultivars, locations and climatic environments will be required to assess the broader applicability of QCAI.

QCAI also clearly distinguished cultivar-level differences in quality-based climate adaptability. Samkwang showed the highest QCAI (0.65), followed closely by Chamdream (0.63), whereas Chilbo showed an intermediate value (0.01). In contrast, Chucheong and Daean showed relatively low QCAI values (–0.60 and –0.69, respectively), indicating poor quality adaptability. Samkwang combined the highest head rice ratio (88.1%) with low protein content (5.1%), which contributed to its high overall quality adaptability. Chamdream had the lowest head rice ratio but showed the highest palatability value (84.3) and the lowest protein content, suggesting very high overall quality adaptability. These findings show that QCAI effectively integrates variation in head rice ratio, protein content and palatability value and thereby separates cultivars according to their quality-based climate adaptability. This interpretation also agrees with studies showing that high temperature and nitrogen supply under field-warming conditions alter grain storage protein synthesis and chalkiness formation, and that chalky grains generated by high temperature affect not only appearance quality but also the physicochemical properties related to texture and eating quality after cooking (Wang et al., 2021; Nakamura et al., 2022). Therefore, QCAI can serve as a useful complementary index for evaluating combined changes in appearance quality, physicochemical quality and eating quality under high-temperature conditions.

Interannual variability in grain quality differed among cultivars and traits (Table 5). The CV ranged from 9.6 to 16.1% for head rice ratio, from 3.9 to 8.3% for protein content, and from 5.7 to 8.2% for palatability value. Chilbo showed the lowest CV for head rice ratio (9.6%), whereas Samkwang showed the lowest CVs for protein content (3.9%) and palatability value (5.7%) and a relatively low CV for head rice ratio (10.7%). Chamdream also showed a low CV for palatability value (5.9%) but a comparatively high CV for head rice ratio (15.9%). These results show that interannual stability differed among individual grain quality traits and should be evaluated separately from mean QCAI, which represents relative integrated grain quality performance.

Table 4. Mean yield and major yield components of rice cultivars from 2020 to 2025

Cultivar	Panicles per hill (No.)	Spikelets per panicle (No.)	Ripened grain ratio (%)	1,000 brown rice weight (g)	Milling recovery (%)	Rough rice yield (t ha^{-1})	Brown rice yield (t ha^{-1})	Milled rice yield (t ha^{-1})
Chucheong	18.7 ± 2.3*	62.9 ± 5.2	91.6 ± 3.0	21.1 ± 0.6	83.4 ± 1.6	6.55 ± 0.31	5.43 ± 0.28	4.99 ± 0.26
Daean	17.7 ± 2.3	67.4 ± 7.2	87.3 ± 10.0	23.6 ± 0.8	82.1 ± 1.2	6.39 ± 0.20	5.25 ± 0.21	4.83 ± 0.20
Mean (Conventional cultivars)	**18.2****	**65.2**	**89.5**	**22.4**	**82.8**	**6.47**	**5.34**	**4.91**
Samkwang	15.5 ± 1.2	92.9 ± 12.2	91.6 ± 3.0	21.8 ± 0.7	83.3 ± 0.7	7.27 ± 0.30	6.06 ± 0.25	5.58 ± 0.23
Chilbo	21.6 ± 3.1	58.0 ± 8.5	92.3 ± 3.5	22.2 ± 0.5	82.6 ± 1.0	6.62 ± 0.42	5.46 ± 0.39	5.03 ± 0.36
Chamdream	17.3 ± 2.2	85.7 ± 10.0	88.4 ± 4.1	22.4 ± 0.7	82.8 ± 0.8	7.44 ± 0.29	6.16 ± 0.22	5.66 ± 0.21
Mean (Newly developed cultivars)	**18.1**	**78.9**	**90.8**	**22.1**	**82.9**	**7.11**	**5.89**	**5.42**

* Values for each cultivar are presented as means ± standard deviation over the six-year period from 2020 to 2025; ** Group means were calculated from the cultivar means.

Table 5. Mean grain quality traits, interannual variability, and quality climate adaptability index (QCAI) of rice cultivars from 2020 to 2025

Cultivar	Head rice ratio (%)	Protein content (%)	Palatability value	Mean QCAI***	QCAI rank
Chucheong	83.3 ± 13.4 (16.1)*	5.5 ± 0.3 (5.9)	78.4 ± 6.5 (8.2)	-0.60	4
Daean	83.7 ± 9.7 (11.5)	5.6 ± 0.5 (8.1)	79.6 ± 5.9 (7.4)	-0.69	5
Mean (Conventional cultivars)	**83.5****	**5.6**	**79.0**	-0.65b****	**-**
Samkwang	88.1 ± 9.4 (10.7)	5.1 ± 0.2 (3.9)	82.7 ± 4.7 (5.7)	0.65†	1
Chilbo	85.8 ± 8.2 (9.6)	5.3 ± 0.4 (7.4)	80.9 ± 5.1 (6.3)	0.01	3
Chamdream	82.8 ± 13.2 (15.9)	5.0 ± 0.4 (8.3)	84.3 ± 5.0 (5.9)	0.63†	2
Mean (Newly developed cultivars)	**85.6**	**5.1**	**82.6**	0.43a	**-**

* Values for each cultivar are presented as means ± standard deviation over the six-year period from 2020 to 2025; values in parentheses are interannual coefficients of variation (CV, %); ** Group means were calculated from the cultivar means; *** QCAI values represent the mean of annual standardised scores; **** Different lowercase letters in the group mean QCAI column indicate a significant difference between conventional and newly developed cultivar groups by paired *t*-test using annual group mean QCAI values ($P = 0.0023$); † Although Samkwang and Chamdream ranked first and second numerically in mean QCAI, their annual QCAI values did not differ significantly (paired *t*-test, $P = 0.949$).

Relationships between climatic factors and yield and grain quality traits

Pearson correlation analysis showed that none of the relationships between the selected climatic factors and crop traits were statistically significant at $P < 0.05$ (Table 6). Among the grain quality traits, head rice ratio showed the strongest association with climatic conditions, with a negative correlation with mean temperature during the grain-filling period ($r = -0.70$, $P = 0.118$). This result indicates a tendency for head rice ratio to decrease under warmer grain-filling conditions, although the relationship was not statistically significant. Milled rice yield showed a positive correlation with mean temperature ($r = 0.60$, $P = 0.206$) and a negative correlation with precipitation ($r = -0.57$, $P = 0.241$) during the rice-growing season. The relationships of protein content and palatability value with the examined climatic factors were variable and were also not statistically significant. Given the limited number of annual observations, these correlations should be interpreted with caution.

Table 6. Pearson correlations between climatic factors and annual mean milled rice yield and grain quality traits from 2020 to 2025

Trait	Climatic period	Mean temperature	Precipitation	Solar radiation
Milled rice yield	Rice-growing season	0.60 (0.206)	−0.57 (0.241)	−0.36 (0.478)
Head rice ratio	Grain-filling period	−0.70 (0.118)	0.22 (0.678)	−0.12 (0.819)
Protein content	Grain-filling period	0.13 (0.805)	−0.38 (0.458)	0.63 (0.178)
Palatability value	Grain-filling period	−0.08 (0.874)	0.48 (0.341)	−0.58 (0.224)

Values are Pearson correlation coefficients (r), with two-sided *P* values in parentheses. Correlations were calculated using six annual observations (2020–2025), with trait values averaged across the five cultivars within each year. Milled rice yield was correlated with climatic variables during the rice-growing season (21 April–20 October), whereas grain quality traits were correlated with climatic variables during the grain-filling period (16 August–20 October). No correlation was statistically significant at $P < 0.05$.

Comparison of yield- and quality-based climate adaptability indices

Table 7 compares the conventional yield-based climate adaptability index with QCAI and again highlights the superiority of the newly developed cultivars. In the yield-based climate adaptability index, Chamdream ranked first (1.17), followed by Samkwang (1.04), Chucheong (0.56), Chilbo (0.36) and Daean (0.27). In contrast, QCAI ranked Samkwang first (0.65), Chamdream second (0.63), Chilbo third (0.01), Chucheong fourth (-0.60) and Daean fifth (-0.69). Although Samkwang had a numerically higher mean QCAI than Chamdream (0.65 vs. 0.63), the difference between their annual QCAI values was not statistically significant (paired *t*-test, $P = 0.949$). Therefore, their ranks should be interpreted as descriptive numerical ordering rather than evidence of a significant difference in QCAI. Thus, Chamdream showed the highest yield adaptability and also maintained a high level of quality adaptability, whereas Samkwang combined high yield adaptability with high quality adaptability. Chilbo showed intermediate levels of both yield and quality adaptability but ranked lowest among the newly developed cultivars. Chucheong and Daean ranked low in both indices, indicating low yield performance and lower integrated grain-quality performance under recent climatic conditions. Daean, in particular, showed the lowest values in both indices and therefore appears to be the most vulnerable cultivar under recent climate change conditions.

Table 7. Comparison between the yield-based climate adaptability index and the Quality Climate Adaptability Index (QCAI)

Cultivar	Mean milled rice yield (t ha^{-1})	Yield-based climate adaptability index*	Yield adaptability rank	Mean QCAI**	QCAI rank	Interpretation
Chucheong	4.99	0.56	3	-0.60	4	Moderate yield adaptability but relatively low quality adaptability
Daean	4.83	0.27	5	-0.69	5	Lowest adaptability in both yield and quality under recent climatic conditions
Mean (Conventional cultivars)	**4.91**	**0.42**	**-**	**-0.65**	**-**	**Lower overall adaptability than newly developed cultivars**
Samkwang	5.58	1.04	2	0.65	1	High adaptability in both yield and quality
Chilbo	5.03	0.36	4	0.01	3	Intermediate adaptability, but the lowest among the newly developed cultivars
Chamdream	5.66	1.17	1	0.63	2	Very high adaptability in both yield and quality
Mean (Newly developed cultivars)	**5.42**	**0.86**	**-**	**0.43**	**-**	**Higher overall adaptability than conventional cultivars**

* Higher values of the yield-based climate adaptability index indicate greater yield adaptability under recent climatic conditions; ** Higher values of QCAI indicate greater quality adaptability under recent climatic conditions.

The comparison of group means between conventional and newly developed cultivars supports the same interpretation. The conventional cultivar group had a mean milled rice yield of 4.91 t ha^{-1}, a yield-based climate adaptability index of 0.42 and a mean QCAI of –0.65, whereas the newly developed cultivar group showed values of 5.42 t ha^{-1}, 0.86 and 0.43, respectively. These values indicate that the newly developed cultivars not only produced higher yields under recent climatic conditions in central Korea but also showed more favourable integrated grain-quality performance. Although the yield-based climate adaptability index and QCAI showed broadly similar trends, the cultivar rankings did not completely coincide. This discrepancy suggests that yield adaptability and quality adaptability represent different aspects of cultivar adaptability under recent climatic conditions. In this context, QCAI provides additional information on grain quality responses that are not fully represented by yield performance alone. Previous studies have likewise emphasised that cultivar evaluation for climate change adaptation should consider not only yield performance but also quality stability, including milling quality and chalkiness occurrence (Sreenivasulu et al., 2015). In Japan, researchers developed a statistical model to estimate the first-grade rice ratio using post-heading high temperature (Fukui et al., 2019), and climate change impact assessments that incorporated the combined effects of temperature and CO_2 concentration also highlighted the need to evaluate grain quality responses such as chalkiness in addition to yield (Ishigooka et al., 2021). Studies on japonica rice in Japan further showed that heat-stress-tolerant cultivars produce lower chalky grain ratios than heat-sensitive cultivars under high-temperature conditions during maturation, confirming that quality responses to heat differ among cultivars (Tanamachi et al., 2016).

Taken together, these findings show that cultivar selection for climate change adaptation should incorporate quality-based indices such as QCAI in addition to conventional yield-centred evaluation. Such an approach enables a more comprehensive assessment that considers both production-oriented cultivation stability and consumer-oriented grain quality. This view also agrees with reports that breeding and introduction targets for heat-tolerant rice cultivars should be defined quantitatively under warming conditions and that reducing high-temperature-induced chalkiness should become an important breeding target (Masutomi et al., 2023). In this context, the present results provide useful evidence for cultivar replacement, particularly for substituting cultivars such as Daean that have shown reduced cultivation stability under recent climatic conditions.

CONCLUSIONS

This study developed and evaluated a Quality Climate Adaptability Index (QCAI) that integrates head rice ratio, protein content and palatability value to complement conventional yield-based evaluation of rice cultivar adaptability. The results showed that Samkwang and Chamdream maintained relatively high yield performance and quality adaptability under recent climatic conditions in central Korea, while Chilbo showed intermediate overall adaptability. Chucheong showed relatively lower quality adaptability despite moderate yield adaptability, whereas Daean showed the lowest values in both yield- and quality-based climate adaptability indices.

The findings indicate that cultivar selection under climate change should consider not only yield stability but also grain quality stability. This is particularly important for table rice cultivars, for which marketability and consumer acceptance depend strongly on appearance quality, physicochemical quality and eating quality.

The present study demonstrates that combining QCAI with conventional yield-centred evaluation can provide a more balanced framework for rice breeding and cultivar selection. This approach may help identify cultivars that maintain both productivity and grain quality under increasing climatic variability. Future studies should expand the number of cultivars and the duration of multi-year trials and further test the applicability of QCAI under a wider range of climatic conditions.

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DECLARATION OF AI USE. Perplexity was used only to support reference search, and Grammarly was used only to refine the English language, including grammar and style, during manuscript preparation. All AI-assisted outputs were reviewed and verified by the authors. The authors take full responsibility for the scientific content, data analysis, interpretation of the results and the final manuscript. No AI tools were used to generate data, fabricate references, or replace scholarly analysis.

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