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Exploring the Production Potential and Adaptability of Black Rice Across Bhutanese Agroecological Zone

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Abstract

Black rice is a nutrient-rich, pigmented rice variety with high health-promoting properties, yet its cultivation and adaptability in Bhutan remain largely unexplored. This study evaluated the production potential and adaptability of black rice across four agroecological zones in Bhutan over four years (2021–2024), using research stations and on-farm trials. Experiments included Single plots evaluation for first three years in the research Centre and Randomized Complete Block Designs in the final year. at research centers and single-plot in the final year, with growth and yield parameters recorded, including tillers per hill, plant height, panicle length, days to maturity, and grain yield. Results indicated significant variation (P ≤ 0.05) in growth and yield across locations, with the highest grain yields observed in dry sub-tropical (Bajo, 2033.31 ± 199.41 kg/acre) and humid sub-tropical (Lingmethang, 1819 ± 282.01 kg/acre) zones, while wet sub-tropical (Samtenling) and highland dry sub-tropical (Tsirang) zones showed lower yields. Black rice exhibited longer maturity periods, fewer tillers, and taller plants compared to improved and local varieties. On-farm trials confirmed that favorable valley conditions in low- to mid-altitude regions support optimal growth and yield. The study demonstrates that black rice can adapt beyond its native southern belt, offering a viable, nutrient-dense alternative for Bhutanese farmers. Strategic promotion and market development are recommended to maximize its economic and nutritional potential.

Keywords: *Black Rice; Agroecological Zones; Yield Performance; Adaptability*

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1 Introduction

Rice is the staple food in Bhutan and has historically played a vital role in the country's food security and livelihoods, while remaining closely interwoven with its culinary traditions, cultural heritage, and religious practices. The current estimated per capita consumption is 144 Kg per year. Rice is grown about 23,289.59 acres with the production of 40,804 MT (National Statistics Bureau [NSB], 2024). Over the years, various research centers have introduced and developed over 31 improved, high yielding and disease resistant rice varieties which are made available to the farmers (Department of Agriculture, 2024). However, the overall adoption rate of these cultivars remains around 42% (Ghimiray, 2013).

Alongside these improved varieties, Bhutan also cultivates traditional rice landraces that form an integral part of its rice farming. The traditional Bhutanese rice varieties can be broadly classified as "Bja Maap" (red pericarp varieties) and "Bja Kaap" (white pericarp varieties) (Wangmo, 2019). Of the pigmented rice varieties, black rice has received increasing attention due to its sensory characteristics, its high nutritive value and, mainly, because of its beneficial health properties (Ito & Lacerda, 2019) but still unknown to Bhutanese consumers and growers. Black rice belongs to *Oryza sativa* L., the same species as white rice and red rice (Pratiwi & Purwestri, 2017). Black rice, often referred to as "Forbidden Rice" or "Emperor's Rice," has an uncertain origin but is known to have originated in Asian countries such as China, India, Japan, and Vietnam (Panda et al., 2022). Historically, it was reserved exclusively for emperors and royal families in ancient China, with severe consequences for unauthorized consumption (Sah & Kushwaha, 2016). Also called "Purple Rice" due to its deep purple-black hue, this rice holds both cultural and nutritional significance. Black rice is a rich storehouse of fibers, vitamins, minerals, proteins, and bioactive compounds, making it a valuable addition to the daily diet. Its incorporation not only promotes overall health but also helps reduce the risk of several diseases such as cancer, inflammation, atherosclerosis, obesity, diabetes, constipation, and hepatic disorders (Das, 2023; Sharma, 2024).

Although black rice has been cultivated in small pockets along Bhutan's southern borders with India, its presence within the country remains minimal. Despite its recognized nutritional and cultural value globally, no systematic studies have yet been carried out to evaluate its performance or adaptability under Bhutanese conditions. Considering Bhutan's rice heritage and the rising interest in pigmented rice, this study aims to evaluate the production feasibility of black rice across different agroecological zones.

2 Materials and Method

2.1 Study Sites and Agroecological Zones

The agroecological zones of Bhutan are subcategorized into six major groups corresponding with altitude and climatic conditions (Table 1). These study sites fall under dry, humid, and wet subtropical zones. Temperate and alpine regions were excluded, as rice is not grown in these areas and moreover black rice is native to the wet subtropical zones.

Table 1. Major agroecological zones of Bhutan

Agroecological Zones	Altitude (masl)	Temperature (˚C)		Mean Rainfall (mm)	Proportion of Geographical Area (%)
		Max	Min		
Alpine	3500–7500	12.0	-1.0	<650	28.6
Cool temperate	2600–3600	22.0	1.0	650–850	23.9
Warm Temperate	1800–2600	26.0	1.0	650–850	18.6
Dry Sub-tropical	1200–1800	29.0	3.0	850–1200	13.1
Humid Sub-tropical	600–1200	33.0	5.0	1200–1500	10.2
Wet Sub-Tropical	100–600	35.0	12.0	2500–5500	5.0

Source: RNR Research Strategy and Plan Document (May 1992)

At Bajo, the trial was conducted in the research farm at an altitude of 1200 masl. Bajo is located at latitude 27°29'25"N and longitude 89°53'58"E. The site represents a dry Sub-tropical agroecological zone is characterized by warm summers and cool making frost possible in the coldest months.

The dry-subtropical AEZ (13% of the country’s area) is dominated by rice as the main summer crop followed by wheat, mustard and vegetables. Improved crop varieties and use of fertilizers and herbicides are gaining popularity; however, farmyard manure is still applied. High crop yields are obtained compared to other agricultural ecological zones (International Center for Tropical Agriculture [CIAT] & World Bank, 2017). The soils at the Bajo are mainly coarse or fine loamy. Organic carbon is 0.1–1.1% with C:N ratios 3.3–50, and available phosphorus is low to moderate (1–5 ppm), making the soils suitable for crop growth with proper nutrient management (NSSC, 2004). The mean minimum temperature during rice season ranges from 18.7˚C in May to 10.4˚C in November while the mean maximum temperature varies from 28.7˚C in May to 24.8˚C in November. The mean annual rainfall was 557 mm from 2021-2024 (Table 2).

Table 2. Mean temperature and rainfall of trial sites

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Samtenling (370 masl): Data from 2023-2024												
Mean Rainfall (mm)	0	6.4	167.5	180.5	362.7	973	1171.1	1383.8	433.4	269.1	6.2	7.7
Mean Max. Temp. ˚C	23.8	24.2	27.3	30.4	31	30.8	32.2	31.6	34	30.9	29.9	26
Mean Min. Temp. ˚C	12.8	13.1	18.4	21.5	23.2	23.8	24.4	24.1	24	21	17.4	14.5
Bajo (1200 masl): Data from 2021-2024												
Mean Rainfall (mm)	2.4	4.6	39.7	18.9	44.4	59.9	106.7	119.6	87.1	69.4	0.8	3.8
Mean Max. Temp. ˚C	19.9	20.4	24.9	27.8	28.7	29.5	30.4	29.7	30.0	27.8	24.8	21.7
Mean Min. Temp. ˚C	6.6	8.3	11.9	15.2	18.7	22.0	22.4	22.1	20.7	16.9	10.4	7.4
Lingmithang (650masl): Data from 2023-2024												
Mean Rainfall (mm)	1.8	4.7	54.6	14.8	55.0	96.0	99.5	108.6	50.9	65.8	0.0	1.8
Mean Max. Temp. ˚C	13.5	17.1	19.3	26.6	30.3	31.5	34.1	33.3	35.9	34.0	34.8	20.4
Mean Min. Temp. ˚C	9.9	11.9	16.3	20.1	21.8	25.3	25.1	25.7	26.0	22.3	16.4	12.8
Tsirang (1480 masl): Data from 2021-2024												
Mean Rainfall (mm)	4.3	11.0	42.1	41.6	54.5	346.2	272.7	340.7	151.5	105.0	0.8	2.7
Mean Max. Temp. ˚C	15.2	15.8	19.5	21.6	22.5	23.3	24.1	24.3	24.9	22.6	20.5	18.1
Mean Min. Temp. ˚C	5.6	6.8	10.5	13.1	15.1	18.8	19.6	19.4	18.6	15.6	9.6	7.4

Data Source: National Center for Hydrology and Meteorology

At Samtenling, the trial was conducted in the research farm at an altitude of 370 masl. It is located at latitude 26°54'26"N and longitude 90°25'52"E. The site represents a wet Sub-tropical agroecological zone are located in the Himalayan foothills in the southern belt and are characterized by high humidity and heavy rainfall making it one of the most precipitation-rich areas in the country. Agriculture is the predominant land use in this zone, with rice being the staple crop. However, due to higher rainfall and humidity there are more insect and disease problems in crops. Other crops include maize, mustard, legumes, and various vegetables. In addition to these, citrus fruits, particularly mandarin oranges, are significant cash crops in the region. Largescale winter cropping although technically feasible is normally not practiced due to the scarcity of water.

The top soils at the Samtenling Research and Development Centre are coarse-loamy with common distinct reddish-brown color. It is very acidic with a pH of 5.40 and generally exhibits very low to low inherent fertility. Total nitrogen is low (0.15%), while organic carbon is moderate (1.60%). In contrast, available phosphorus is very high at 68.0 ppm. (NSSC, 2001). The mean minimum temperature during the rice season ranges from 23.8˚C in

June to 17.4˚C in November while the mean maximum temperature varies from 30.8 ˚C in June to 34˚C in November. The mean annual rainfall was 4961.2 mm from 2023-2024 (Table 2).

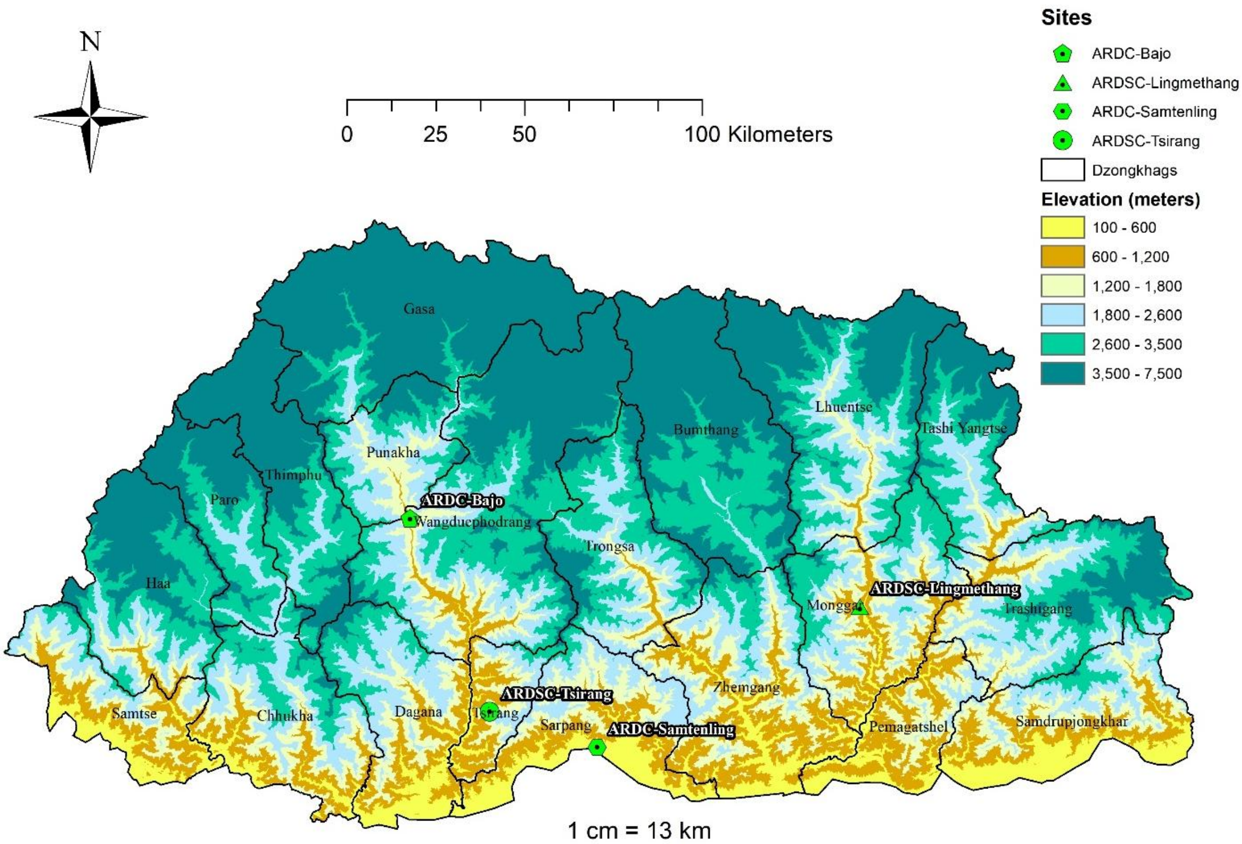

Figure 1. Agroecological zone map of Bhutan with the location of the study sites.

At Lingmethang, the study site is at 27°15'38"N and between 91˚ 10’ 38” and 91°10'45"E at an altitude of 650 masl. It represents a humid -subtropical agroecological zone. Maize and potato intercropping is Very popular. Farmers also cultivate different vegetables, grain legumes, millet, buckwheat, barley and mustard in the dryland (Katwal, 2020). The soils at Lingmethang are mainly sandy loams and sandy clay loams, slightly acidic to neutral (pH 6.32–7.01). The organic carbon and total nitrogen are generally low to moderate and the overall fertility potential and inherent fertility is categorized as slightly poor (NSSC,2003). The mean minimum temperature during rice season ranges from 25.1˚C in July to 12,8˚C in December while the mean maximum temperature varies from 34.1˚C in July to 20.4˚C in December. The mean annual rainfall was 553.4 mm from 2023-2024 (Table 2).

At Tsirang, the study site was at Menchuna ARDSC suited at 26°59'52"N and 90°07'32"E at an altitude of 1480 masl. It represents a dry-subtropical agroecological zone but features a temperate highland tropical climate with dry winters and the wet season is warm, humid, and mostly cloudy. sirang grows a diverse range of crops, including staple cereals like paddy and maize, as well as cash crops such as chili, orange, and cardamom. The soils are mostly sandy loam and slightly acidic (pH 5.01–5.53) with low to moderate organic carbon (0.23–0.58%) and mostly low nitrogen. Available phosphorus and potassium are generally low, giving the soils a low to moderate fertility potential. The mean minimum temperature during rice season ranges from 15.1˚C in May to 9.6˚C in November while the mean maximum temperature varies from 22.5˚C in May to 20.5˚C in November. The mean annual rainfall was 1372.8 mm from 2023-2024 (Table 2).

2.2 Experimental Design

The study was conducted as a Nationally Coordinated Trial (NCT) over four years (2021–2024) at four research centers namely Agriculture Research and Development Centre (ARDC) and Samtenling, Agriculture Research and Development Sub-Centre (ARDSC) Lingmithang, and Tsirang (Figure 1). In its final year, the trial was extended to farmers' fields across multiple locations, including Zomi, Toedwang, and Chubu Gewogs in Punakha District, and Daga, Athang, and Rubesa Gewogs in Wangdue Phodrang District. The trial initially began at ARDC Bajo and ARDSC Tsirang in 2021, and was later expanded to ARDC Samtenling and ARDSC Lingmithang in 2023 and 2024.

For the first three years, all experiments were conducted in large single plots evaluate the feasibility and performance of black rice under different study area. In 2024, the evaluation was carried out using a Randomized Complete Block Design (RCBD) with three treatments and five replications. The treatments included one improved variety and one local variety used as checks. Each replication formed a block to account for field variability, and treatments were randomly assigned to plots within each block using a random number table. Each plot measured 2 m × 3 m (6 m²), accommodating 96 hills (12 columns × 8 rows) with 25 cm × 25 cm spacing between hills. Plots were separated by 40 cm to minimize inter-plot interference. In 2024, single-plot trials were conducted in farmers' fields to assess the feasibility and performance of black rice under real field conditions.

2.3 Crop management

Healthy seeds of black rice, sourced from Nganglam, Pemagatshel, were sown at a rate of 25 kg per acre. Seedlings were transplanted into the well-puddled experimental plots, and recommended fertilizer rates (30-20-8 kg NPK per acre) were applied. Weeds were controlled through two hand weeding. The crop of each plot was harvested separately at full maturity when 90% of the grains turn golden yellow in color on different dates.

2.4 Data collection

For data collection five plants sample per a plot were selected randomly for the yield parameters such as Tillers /hill, Plant height (cm), Panicle length (cm), Grain /panicle (No) and Empty grain/panicle. Moisture content was measured using digital grain moisture meter at the time of crop harvest and fresh weight of grains of each plot were converted into grain yield ton per acre after adjusting the moisture content at 14% using the formula (1). Straw obtained from each crop cut were weighed separately in kg and finally converted into straw yield ton per acre. Harvest index is the ratio of economic yield to biological yield and was calculated with the formula (2). To measure yield in the farmers field, three crop cuts were taken from an area 6 m^2. Threshing was done manually.

$$Adjusted\ yield\ (kg/acre) = \left(\frac{100 - MC_{field}}{100 - MC_{standard}}\right) * \frac{Yield\ per\ plot (kg)}{plot\ size\ (\mathrm{m}^2)} * 4046.86 \ldots (1)$$

Where MC_{field} is moisture content (%) of the sample at harvest

$$Harvest\ Index\ (\%) = \frac{Grain\ yield\ (kg/acre)}{Grain\ yield (kg/acre) + straw\ yield\ (kg/acre)} * 100 \ldots\ldots\ldots (2)$$

2.5 Statistical Analysis

The data for the 2024 trial were analyzed using the statistical software Statistix 8.1. Analysis of variance (ANOVA) was used to compare means, with the level of significance set at 5% ($p \leq 0.05$).

For the analysis of data spanning four years, analyses were conducted in R software using the lme4 (Bates et al., 2015) and emmeans (Lenth, 2024) packages. The lme4 package is used for fitting linear and generalized linear mixed-effects models, which allow the inclusion of both fixed and random effects and can handle unbalanced datasets. The emmeans package is used to estimate marginal means (least-squares means). A mixed-effects model was applied to assess the effect of location on rice traits over multiple years, accounting for unbalanced data. Location was treated as a fixed effect, while year was included as a random effect. ANOVA was performed within the mixed-model framework using Satterthwaite's approximation to obtain appropriate degrees of freedom and to test the significance of location effects. Estimated means with standard errors (Mean ± SE) were calculated, and pairwise comparisons between locations were performed using the LSD test.

The effect of rainfall and temperature on rice yield was analyzed using a linear mixed-effects model, with rainfall and temperature included as continuous fixed effects and location and year as random effects. The significance of fixed effects was tested using ANOVA with Satterthwaite's approximation.

3 Results and Discussion

3.1 Multi-Year Performance Across Agroecological Zones

3.1.1 Yield

The result showed significant differences for the grain yield ($P \leq 0.05$) across the sites (Table 3). The observed grain yields ranged from 519.06 to 2033.31 kg/ac, with the highest yields recorded at Bajo (dry sub-tropical, 10.4–28.7 ˚C, 557 mm rainfall) and Lingmethang (humid sub-tropical, 12.8–34.1 ˚C, 553.4 mm rainfall), where moderate temperatures and rainfall favored good crop growth and grain development. In contrast, very high rainfall at Samtenling (wet sub-tropical, 17.4–34 ˚C, 4961.2 mm) and cooler conditions at Tsirang (dry sub-tropical highland, 9.6–22.5 ˚C, 1372.8 mm) limited yield. Despite being grown for the first time in the experimental sites, black rice produced appreciable yields.

Notably, the observed yields not only match but, in places like Bajo, exceed the recent national average rice productivity in Bhutan of about 1800 kg/ac (National Statistics Bureau, 2024). The results show the good potential of black rice, especially in low- to mid-altitude regions, although generally, black rice was grown in lowland about 0-600masl. Comparable productivity has been reported internationally, with yields ranging from 1941 kg/acre in India (Chandrika et al., 2024), 2,084 kg/ac in Indonesia (Herliana et al., 2019) and 850–1011 kg/ac in Nepal (Khadka, 2016) indicating that the performance of black rice in Bhutan is consistent with its potential in other Asian contexts. It is considered comparatively less productive than the other rice varieties under normal condition (Borah et al, 2018). Though lower productivity, higher prices are the reason behind in accessibility of nutrient enriched black rice by common people (Tiwari, 2022).

Table 3. Growth and yield performance of black rice across four locations

Location	Altitude (masl)	Years	Tillers (Nos)	Plant height (cm)	Panicle length (cm)	Maturity days	Yield (Kg/ac)
Bajo	1200	2021-2024	10.69 ± 1.26[a]	135.91 ± 4.57[b]	19.88 ± 0.66[a]	150.25 ± 9.38[a]	2033.31 ± 199.41[c]
Lingmithang	650	2023-2024	15.43 ± 1.67[b]	136.64 ± 6.46[b]	23.23 ± 0.93[b]	148.12 ± 12.95[ab]	1819 ± 282.01[bc]
Samtenling	370	2023-2024	10.36 ± 1.67[ab]	132.12 ± 6.46[b]	22.95 ± 0.93[b]	139.62 ± 12.95[a]	519.06 ± 282.01[a]
Tsirang	1480	2021-2024	9.28 ± 1.26[a]	103.03 ± 4.57[a]	22.7 ± 0.66[b]	183.75 ± 9.38[b]	1038.63 ± 199.41[ab]
p-value			0.0744	0.0032	0.0343	0.0624	0.0073

* The values presented are estimated marginal means (± SE) obtained via the emmeans package

3.1.2 Number of Tillers

The mean number of tillers across the four study locations varied from 9.28 ± 1.26 to 15.43 ± 1.67, with the highest number recorded at Lingmithang (650 masl) and the lowest at Tsirang (1480 masl). Although the effect of location on tiller number was not statistically significant, a general trend of higher tillering was observed in the lowland sites compared with the highland sites. This finding is consistent with the results reported for black rice in Indonesia, where plants grown in highland environments produced fewer tillers than those cultivated in lowland areas (Purwanto, Hidayati, & Nandariyah, 2018).

3.1.3 Maturity durations

Maturity duration of rice varied across the four locations, ranging from 139.62 ± 12.95 days at Samtenling to 183.75 ± 9.38 days at Tsirang, with Bajo and Lingmithang showing intermediate values (Table 3). Although the differences were marginally non-significant ($p = 0.0624$), the observed variation reflects meaningful environmental influences, particularly altitude and temperature. Shorter maturity at Lingmithang and Samtenling likely resulted from warmer conditions that accelerated plant development, whereas cooler conditions at Tsirang delayed crop maturity. Similar trends were reported by Khanum et al. (2023), where the same rice varieties exhibited different days to maturity across three agroecological zones in Bangladesh, with cooler, higher-altitude regions delaying maturity and warmer, lowland areas accelerating it. Black rice could be categorized as a long-duration cultivar as related by

Nandariyah (2023), black rice, being a landrace, generally has cultivation challenges such as a prolonged vegetative phase and high habitus.

3.1.4 Plant height

Plant height differed significantly among locations (($P \leq 0.05$) (Table 3). Tsirang recorded the shortest mean height (103.03 ± 4.57 cm), while the other three locations had taller plants, ranging from 132.12 to 136.64 cm. Comparatively, black rice plant height has been reported to range from 141–146 cm in India (Sangma et al., 2022), 157.34–164.68 cm in the Philippines (Menardo et al., 2024), and 109.7–114 cm in Egypt (Metwally, 2024). These findings are consistent with observations reported by Tahir et al. (2002) who noted that plant height is primarily determined by the genetic makeup of the cultivar, though environmental factors also play a significant role.

3.1.5 Panicle length

Panicle length differed significantly among locations (($P \leq 0.05$), with the highest at Lingmithang (23.23 ± 0.93 cm) and the lowest at Bajo (19.88 ± 0.66 cm). Samtenling (22.95 ± 0.93 cm) and Tsirang (22.7 ± 0.66 cm) were intermediate (Table 3). These results are consistent with previous studies in Indonesia, where Sudarmayanti et al. (2022), reported that panicle length in rice is strongly influenced by environmental conditions. Notably, one of their experimental sites, Tampak Siring (379 masl), showed a panicle length (22.33 cm) similar to Samtenling (370 masl) in the present study, suggesting that altitude and related environmental factors may have comparable effects on panicle development. Sarker et al. (2011) also reported differences in number of panicles due to climatic parameters. As cited in Sofian et al. (2019), panicle length is one of the important parameters determining the productivity of a rice variety, because longer panicles produce a greater number of grains, which increases the grain weight per plant and can enhance overall rice productivity.

3.1.6 Effect of rainfall and temperature on yield

The effects of rainfall and temperature on rice yield were assessed using a linear mixed-effects model with location and year as random effects (Table 4). Rainfall showed a negative association with yield (estimate = −0.36), suggesting that yield tended to decrease with increasing rainfall. while temperature showed a positive association (estimate = 96.57), indicating a tendency for higher yields at higher temperatures. However, neither effect was statistically significant. The relationships between rice yield and rainfall and temperature are further illustrated in Figures 2 and 3, respectively.

Table 4. Linear mixed-effect regression

Predictor	Estimate	Std. Error	df	t value	p-value
Rainfall	-0.36	0.12	1.40	-2.98	0.14
Temperature	96.57	70.31	1.03	1.37	0.39

Random-effects analysis revealed variability among locations (variance = 67,842.25), whereas inter-annual variability was negligible (variance = 0), suggesting that agro-ecological differences had a much greater influence on rice yield than year-to-year climatic variation.

Although black rice is grown in the southern belt and across the border in India, yield at Samtenling was low. Samtenling received much higher rainfall (5,376 mm in 2023, 4,540 mm in 2025) than Bajo (449 mm; 575 mm). Consistent with the observed negative relationship between rainfall and yield and the positive relationship with temperature, this poor performance can be associated with excessive rainfall under warm wet sub-tropical conditions, which likely constrained yield. In contrast, mid-altitude locations, receiving more moderate rainfall and favorable thermal conditions, achieved higher yields. Overall, the results indicate that rainfall extremes within the southern belt can suppress rice yield, explaining the unexpectedly poor performance at Samtenling.

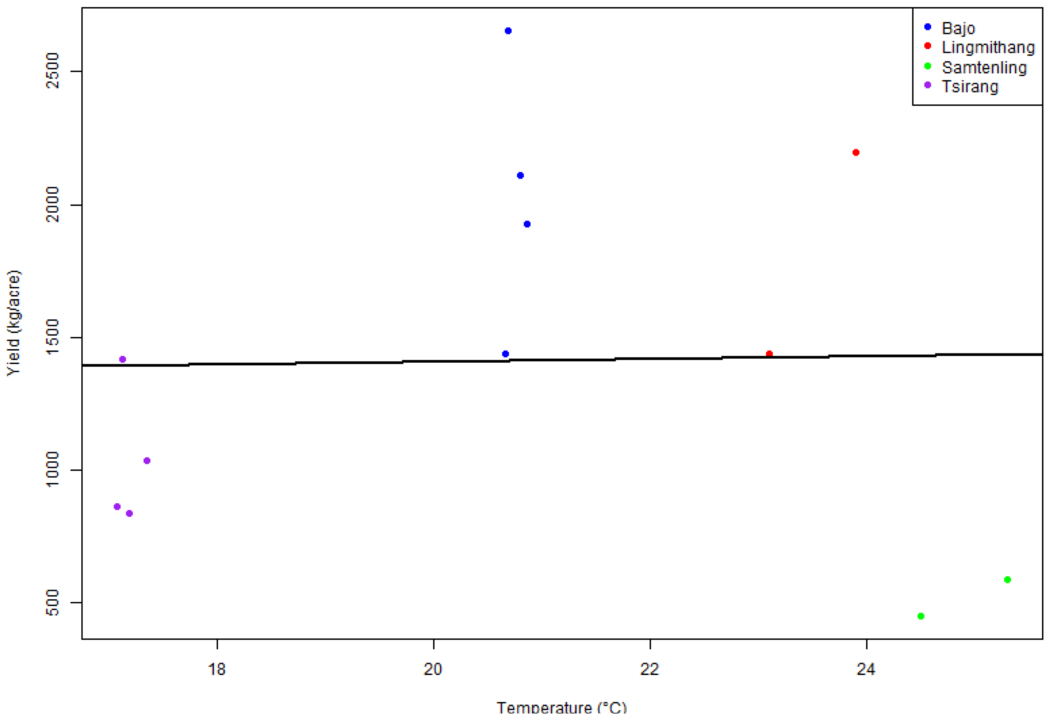

Figure 2. Scatter plot showing effect of temperature on yield

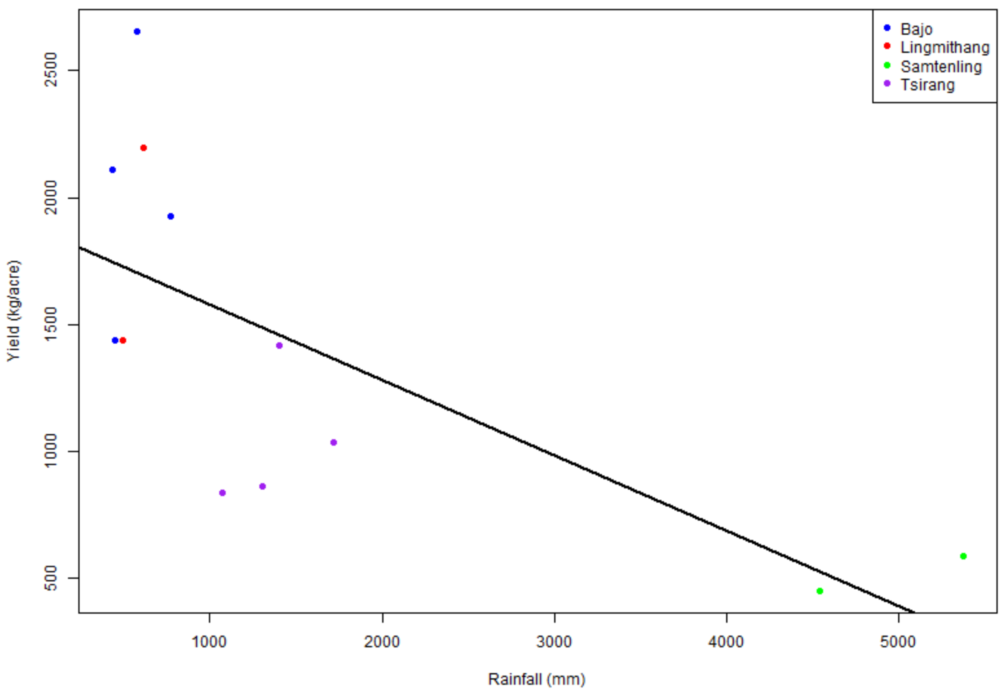

Figure 3. Scatter plot showing effect of rainfall on yield

3.1.7 Varietal Comparison (2024 RCBD)

The ANOVA result (Table 5) shows that significant differences were observed among the three varietal groups across most traits and locations. Black Rice generally produced fewer tillers per hill, for instance, 9.76 in ARDC Bajo and 6.13 in ARDSC Tsirang, compared to local varieties which reached up to 28.05 (Tsirang Zam) and improved varieties with 17.00 (BK3). Plant height of Black Rice was intermediate to high, such as 143.64 cm in Bajo and 142.23 cm in Samtenling, often taller than improved varieties like 128.12 cm (IR20913) and 87.33 cm (BK3), but shorter or comparable to local varieties such as 147.68 cm (Khamtey) and 183.11 cm (Tsirang Zam). Panicle length of Black Rice tended to be slightly shorter than local varieties (19.90 cm in Bajo vs. 23.46 cm for Khamtey) but similar to improved ones like 22.58 cm (IR20913).

In terms of yield, Black Rice consistently produced lower yields, 2655.90 kg/acre in Bajo and 1034.00 kg/acre in Tsirang, compared to local varieties which achieved up to 4181.10 kg/acre (Khamtey) and improved varieties with 2996.50 kg/acre (IR20913). The differences in yield were statistically significant across all locations ($P \leq 0.05$), highlighting that local and improved varieties consistently outyield Black Rice. Days to maturity for Black Rice were generally longer than improved varieties, such as 194 days in Bajo vs. 163 days for IR20913, but varied when compared with local cultivars (174 days for Khamtey).

These results are acceptable and consistent with the known characteristics of Black Rice. Its lower yield, prolonged vegetative phase, and tall stature are inherent unfavorable traits. Being a low-yielding crop (approximately 10% relative to other rice types; Bolay, 2021), Black Rice is naturally rarer and considered less productive under normal cultivation conditions.

Table 5. Comparative performance of black rice, improved, and local varieties across four locations in 2024

Location	Variety	Tillers/hill (Nos.)	Plant Height (cm)	Panicle Length (cm)	Days to Maturity	Yield (kg/acre)
ARDC Bajo	Black Rice	9.76^{a}	143.64^{a}	19.90^{b}	194	2655.90^{c}
	IR20913 (Improved)	14.32^{a}	128.12^{b}	22.58^{a}	163	2996.50^{b}
	Khamtey (Local)	15.12^{b}	147.68^{a}	23.46^{a}	174	4181.10^{a}
	P Value	0.0001	0.0000	0.0001	-	0.0000
ARDSC	Black Rice	6.13^{b}	92.73^{b}	20.66^{c}	187	1034.00^{c}

Tsirang	Wangkhar Ray Kaap-II (Improved)	7.06[b]	67.60[c]	23.06[b]	172	1465.30[b]
	Chorti (Local)	8.73[a]	129.27[a]	24.73[a]	190	1180.30[a]
	P Value	0.0048	0.0000	0.0000	-	0.0000
ARDSC Lingmithang	Black Rice	16.80[b]	136.27[b]	24.46[b]	156	2199.5[b]
	BK3 (Improved)	17.00[b]	87.33[c]	23.66[b]	145	2776.6[a]
	Tsirang Zam (Local)	28.05[a]	183.11[a]	30.62[a]	150	1940.0[c]
	P Value	0.0000	0.0000	0.0000	-	0.0000
ARDC Samtenling	Black Rice	10.66[a]	142.23[a]	22.31[ab]	148	452.12[b]
	Bhur Raykaap 2 (Improved)	9.26[ab]	114.30[c]	24.00[a]	148	585.83[c]
	Kalo Timburay (Local)	7.06[b]	121.20[b]	21.53[b]	148	322.74[a]
	P Value	0.0961	0.0003	0.0896	-	0.0068
	*Means followed by same letters are not significant different					

3.2 Performance of black rice in the farmers field in 2024

After analyzing the multi-year production trial data, it was observed that black rice performed relatively well at ARDC-Bajo. Given this performance in the dry subtropical region the evaluation was further extended in 2024 to farmers' fields to assess its performance under actual field conditions, particularly in the Bajo area at an altitude of around 1200 masl, encompassing Wangdue and Punakha districts.

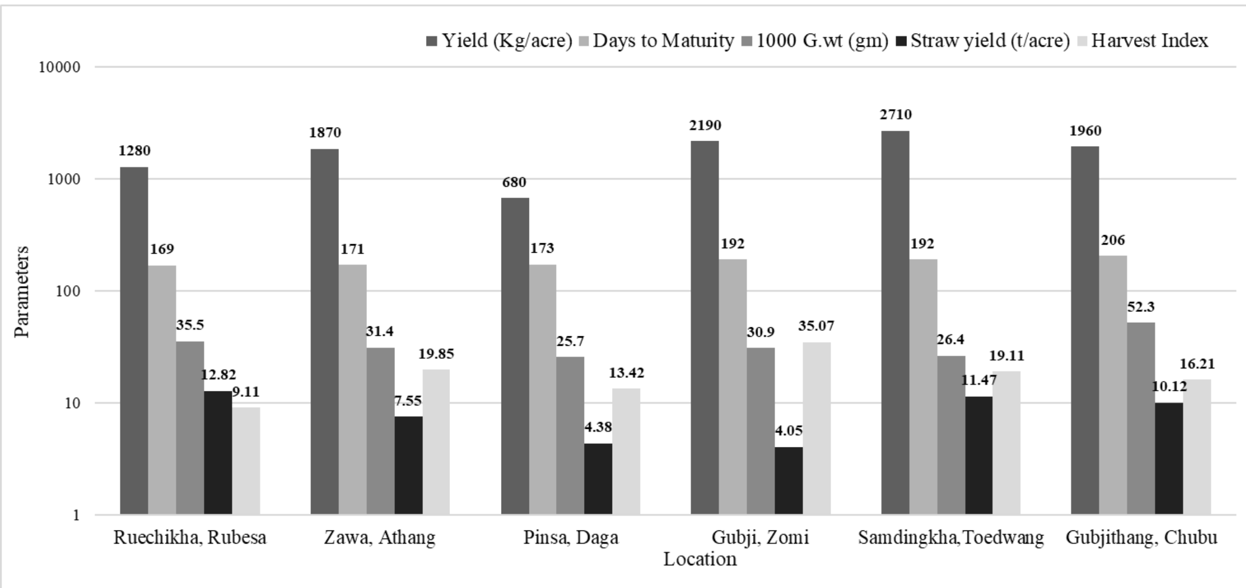

Figure 4. Yield, Days to Maturity, 1000-Grain Weight, Straw Yield, and Harvest Index in farmer's field

The result (Figure. 4) shows that yield of Black Rice across farmers' fields varied widely. Zawa, Athang exhibited the highest number of tillers per hill (11.67), and longest panicle length (23 cm), indicating better vegetative growth and panicle development relative to the other evaluated locations (Figure 5). The highest yields were recorded in Punakha valley sites such as Samdingkha (2710 kg/acre) and Gubji (2190 kg/acre), suggesting that the relatively warm and favorable valley conditions supported better grain filling and productivity. In contrast, yields in sites like Pinsa (778.55 masl) remained low (680 kg/acre), reflecting poor tillering but highest plant height (174.98).

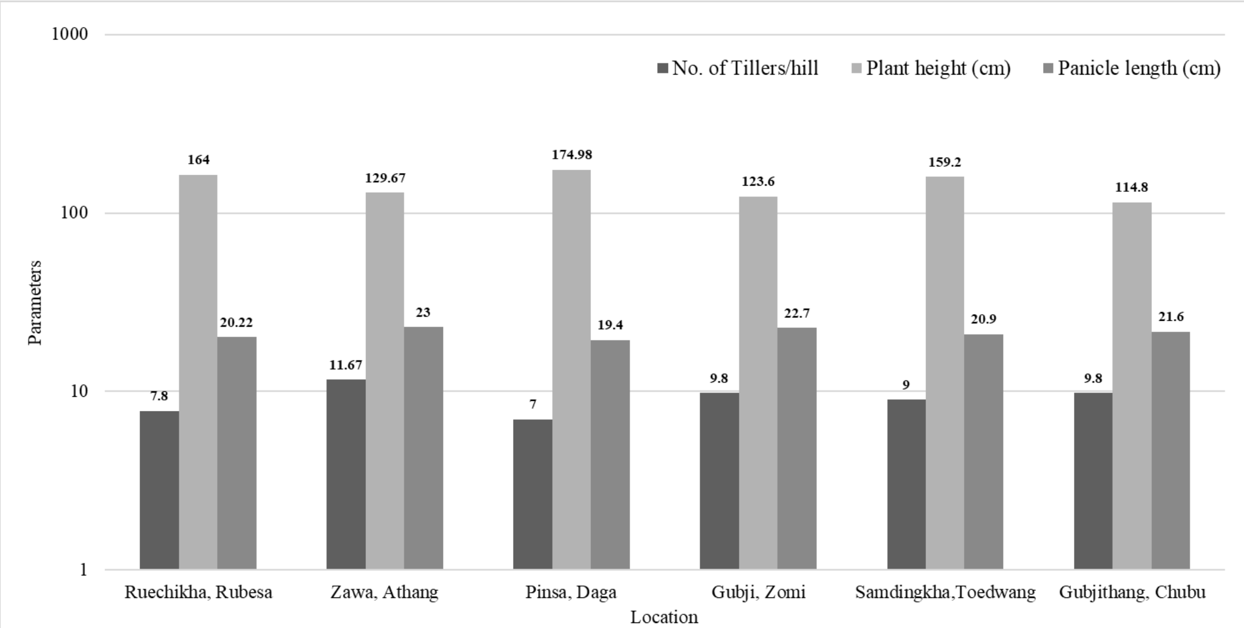

Figure 5. No. of tillers/hill, Plant height, Panicle length in farmer's field

These results highlight the strong influence of location and environment on Black Rice yield. While Punakha sites showed better adaptation, Wangdue Phodrang sites were less productive. Overall, the yield levels observed in farmers' fields (Samdingkha, Toedwang 2710 kg/acre) confirm that the yield were at par to the research station at ARDC- Bajo (2655.9 kg/acre).

3.3 Proximate analysis of black rice vs white rice

Table 6: Comparing the nutrient analysis of black rice with white rice

Sample ID	Total solids	Total ash content	Crude protein	Crude Fat	Total Carb	Energy	N	P	K	Ca	Fe	Vitamin C
Unit	%	%	%	%	%	Kcal/100g	%	ppm	mg	mg	ppm	mg/100g

Black rice	88.14	2.63	8.94	1.75	74.81	350.81	1.43	0.02	8.60	9.00	0.11	0.02
Bk3	96.73	1.22	7.17	0.96	87.38	386.82	1.15	0.01	7.10	9.00	0.19	0.01

The result shows differences in proximate and nutrient composition between black rice and white rice (Bk3). Black rice showed lower total solids but higher ash content than white rice, indicating greater mineral presence. Crude protein and crude fat were also higher in black rice than in white rice. Similar findings have been reported by Abd and Shehata (2010), who observed higher ash, protein, and oil contents in black rice compared to white rice. White rice recorded higher iron content, total carbohydrate content, and energy value (386.82 kcal/100 g) than black rice (350.81 kcal/100 g). Similar findings were reported by Ojha, Mogra, and Kachhawa (2025). Black rice showed higher contents of nitrogen, potassium, phosphorus, and vitamin C, while calcium levels were similar. These findings align with previous reports indicating that, compared to white rice, black rice is richer in minerals such as zinc, iron, phosphorus, and manganese, as well as vitamins including B-complex and E, although vitamin C and calcium were not assessed in that study (Rahim et al., 2022). Overall, the results indicate that black rice provides a more nutrient-dense composition compared to white rice, while white rice serves primarily as an energy source.

3.4 Limitations of studies

- Single-plot data: Observations were collected from a single plot per location, which may limit the generalizability of the findings.
- Limited year coverage: Trials were not conducted uniformly across all years for each location.

4 Conclusion

This study showed that black rice performs best in dry sub-tropical regions such as Bajo (1200 masl), where temperatures and rainfall during the growing season ranged from 10.4–28.7 °C and 557 mm, respectively. It also showed good performance in humid sub-tropical areas like Lingmethang (650 masl), with growing season temperatures of 12.8–34.1 °C and rainfall of 553.4 mm, where relatively higher yields were obtained. Although Tsirang (1480 masl) falls under the dry sub-tropical zone, its higher elevation and other climatic factors likely contributed to its relatively lower performance, while Samtenling (370 masl, wet sub-tropical) exhibited poor adaptation.

These evaluations demonstrate that it can adapt well beyond southern belt, highlighting its strong potential for expansion into other suitable regions of Bhutan. Although black rice is known for certain inherent unfavorable traits, particularly low yield, the evaluation indicates that it has good potential if cultivated under recommended or suitable agro-climatic conditions.

Table 7. Recommended growing season of black rice in different agro-ecological zones

Agroecological zone	Altitude (masl)	Nursery time	Harvest
Dry Subtropical	1200-1800	May	November
Humid Subtropical	600-1200	July	December
Wet Subtropical	100-600	June	November

The cultivation of black rice has been successfully demonstrated to farmers through on-farm trials and can be adopted across suitable agroecological zones, as its package of practices is similar to that of other rice cultivars. Consequently, it has been officially released for cultivation under the recommended growing period (Table 7).

The crop was newly introduced in the trial stations, and it was encouraging to note that farmers were highly receptive to its cultivation. In addition, with the growing trend toward healthier eating habits, black rice fits well as a nutrient-dense and visually distinctive alternative to traditional white rice. Its unique characteristics make it particularly attractive to health-conscious consumers and those seeking premium, specialty food options. Moreover, its lower productivity contributes to higher market prices, restricting access to this nutrient-enriched rice for the general population (Kumari, 2020). However, the market and pricing for black rice in the country remain largely unknown. To fully realize its potential, cultivation efforts should be complemented with proper promotion at the farmers' level, alongside market assessment and strategic planning. Introducing black rice as a nutritious health food could enhance the food and nutritional security of the Bhutanese population. In addition, establishing marketing channels is essential to ensure that farmers can benefit economically from its cultivation.

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6 Authors' contribution statement

Deki Lhamo was responsible for the implementation of the research and data collection at on-farm Bajo and farmers' fields, as well as the analysis and interpretation of results and preparation of the draft manuscript. Cheku Dorji contributed to the implementation of the research and data collection at Bajo. Dolay was involved in the implementation of the research and data collection at Tsirang. Sonam Deki contributed to the implementation of the research and data collection at Lingmethang. Chezang Dendup was responsible for the implementation of the research and data collection at Samtenling.

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