



RESEARCH ARTICLE

Potassium fertilisation scheduling for improved grain yield and antioxidant quality in black rice

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Abstract

Despite the recognised role of potassium (K) in crop productivity, limited research exists on how different K fertilisation schedules influence both grain yield and antioxidant quality in black rice. Therefore, a field study was conducted during kharif 2024 to assess the influence of K fertilisation schedules for improved grain yield and antioxidant status in black rice. The experiment was conducted in a split-plot design, with variety assigned to the main plots and K application schedules to the subplots and was replicated 3 times. Three rice varieties were: BPT 2841 (V_1), Kala Bhat (V_2) and RNR 15048 (V_3). Four K application schedules were: $K_{100-0-0}$ (100 % recommended dose of K (RDK) as basal), $K_{50-50-0}$ (50 % RDK at basal + 50 % at active tillering), $K_{50-0-50}$ (50 % RDK at basal + 50 % at panicle initiation) and $K_{50-25-25}$ (50 % RDK at basal + 25 % at tillering + 25 % at panicle initiation). The data generated from the study concluded that, V_2 recorded the highest available soil K (156.3 kg ha^{-1}), total K content (0.48%) and antioxidant properties (anthocyanin ($57.72 \text{ mg } 100 \text{ g}^{-1}$), flavonoid ($43.28 \text{ mg } 100 \text{ g}^{-1}$) and phenolic ($614.53 \text{ mg } 100 \text{ g}^{-1}$)), while V_3 produced the highest grain yield (4.84 Mg ha^{-1}). Among application timings, the $K_{50-25-25}$ split was most effective, enhancing soil K, total K in grain, yield and antioxidant levels. Three splits of K found were most effective to enhanced both quantity and quality of black rice grain.

Keywords: antioxidants; black rice; potassium; yield

Introduction

Rice (*Oryza sativa* L.) is the staple food for a large proportion of the world's population. At global level, India is the second-largest rice producer, with a production of 135.76 million tonnes, after China, which produced 145.95 million tonnes of rice (1). In India, productivity of white rice is increasing over time, however, improvement in economic conditions as well as awareness of nutritious food and health issues among the Indians restricts the increase in consumption of white rice. Under such a situation, black rice can offer a promising alternative due to its high nutritional value, especially its high antioxidant properties. Thus, black rice can provide good nutrition and health benefits to consumers to satisfy their dietary requirements (2). Cultivation of black rice can also increase the income of the farmers.

In black rice varieties, pigment accumulation in the rice bran layer, leads to the development of pigmented rice with different colour. These pigmented rice varieties are classified as black, red and purple rice according to the content of anthocyanin and proanthocyanidin compounds (3). China holds the most extensive black rice genetic resources, accounting for 62 % of the global share. This is followed by Sri Lanka (8.6 %), Indonesia (7.2 %), India (5.1 %), Bangladesh (4.1 %) and a smaller presence in Malaysia (4). In India, a

wide range of black rice varieties are cultivated locally, particularly in Northeastern states. In Manipur, black rice is popularly known as "Chakhao," a term that means "delicious".

Black rice is a traditional, pigmented, glutinous variety known for its low-fat content (5). It is rich in essential nutrients, including higher concentrations of vitamins, proteins, essential amino acids, various trace elements, dietary fibre and antioxidants such as anthocyanins and phenolic acids (6). The presence of anthocyanins such as cyanidin-3-glucoside and peonidin-3-glucoside is responsible for the distinctive black colour of black rice (6). Tricin, the predominant flavonoid in black rice bran, accounts for approximately 77 % of the total flavonoid content and contributes to antioxidant activity by inhibiting lipid peroxidation, which also contributes to its antioxidant properties (7). The bran extracted from pigmented rice contains significantly higher levels of phenolic compounds (8).

Potassium (K) is an essential primary nutrient required for proper growth and development of plants. Often referred to as the "quality nutrient," K enhances a plant's resistance to various diseases. It also plays a crucial role in regulating water balance and maintaining the structural integrity of cell walls. Inadequate or deficient K levels can lead to stunted plant growth, breaks

chlorophyll structure and causes a significant reduction in yield (9). Potassium contributes to better grain quality and increases the efficiency of water and nutrient utilisation. It also enhances stress tolerance, improves energy use efficiency and facilitates the movement of photosynthates and sugars from the source (leaves) to the sink i.e. grains (10). Potassium applied with nitrogen and phosphorus can positively influence the antioxidant content of black rice (6). Added K increased total phenols strengthening the components of both the enzymatic as well as non-enzymatic antioxidant system of cereals (11). While K is known to influence rice yield, grain quality and antioxidant properties, limited research exists on the effect of split application schedules of K specifically for black rice, a pigmented variety rich in bioactive compounds under field conditions. The lack of information on the most effective timing of K application for maximising both productivity and nutritional quality limits evidence-based nutrient management strategies for this specialty rice. Optimising the timing of K fertiliser application in black rice enhances nutrient uptake efficiency, thereby improving grain yield, yield attributes and antioxidant quality compared to conventional K application practices. The objective of the present study was to identify the optimal K fertilisation schedule for enhancing both grain productivity and the functional food value of black rice under field conditions. It was hypothesised that split application of K would maintain greater K availability during critical crop growth stages, thereby improving grain yield, K accumulation and antioxidant biosynthesis compared with the conventional basal application.

Materials and Methods

A field experiment was conducted at a single location during June to December 2024 (kharif), at the Post Graduate Research Farm of M. S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha. The geographical location of the experimental site was at 18.8045° N latitude, 84.1792° E longitude. The soil of the site was Rhodic paleustalfs, sandy loam in texture (58.2 % sand) with a high saturated hydraulic conductivity value (16.7 mm day⁻¹). The major chemical properties of the soil were as: pH- 5.06, electrical conductivity (EC)- 0.0204, available organic carbon (OC)- 0.45 %, available N, P and K respectively, 203.5, 12.3 and 151.5 kg ha⁻¹. During the growing period, the crop received approximately 381 mm of rainfall during the first 30 days after transplanting (0–30 DAT), providing adequate soil moisture for crop establishment and early vegetative growth. Rainfall gradually declined during the subsequent growth period, with about 304 mm received between 30 and 60 DAT and only about 122 mm during the reproductive stage (60–90 DAT). Thereafter, approximately 338 mm of rainfall was received from 90 DAT until harvest, mainly due to intermittent rainfall events during the later part of the crop growth period. Thus, the crop experienced comparatively higher rainfall during the early vegetative stage, relatively drier conditions during the reproductive phase and moderate rainfall towards maturity.

The field experiment was laid out with a split-plot design. Three rice varieties were placed in main plot treatment and the varieties were: (i) V₁-BPT 2841 (Hybrid black rice), (ii) V₂ - Kala Bhat (Local black rice) and (iii) V₃ -RNR 15048 (High yielding white rice). Four K application timings were assigned to subplots as: K_{100:0:0} (100 % as basal), K_{50:50:0} (50 % as basal + 50 % at active tillering), K_{50:0:50} (50 % as basal + 50 % at panicle initiation) and K_{50:25:25} (50 % as

basal + 25 % at active tillering + 25 % at panicle initiation). A common fertiliser dose, i.e., the recommended fertiliser dose for kharif rice in the region (80 : 40 : 40 kg ha⁻¹ of N : P₂O₅ : K₂O), was applied to all treatments. Nitrogen, phosphorus and K were supplied through urea, single superphosphate (SSP) and muriate of potash (MOP), respectively. Nitrogen was applied in three equal splits, with 50 % as basal, 25 % at active tillering and the remaining 25 % at panicle initiation. Phosphorus was applied entirely as a basal dose, whereas K was applied according to the respective treatment schedules. In any nutrient experiment researchers keep one controlled treatment i.e. crop grown without the application of any nutrient, however in this study the recommended K dose of 40 kg K₂O ha⁻¹ applied 100 % as basal was considered as the check. Each treatment was replicated thrice.

During the study period, available soil K and total plant K content were estimated using standard protocols explained in Eqs. 1 and 2 as described by previous researchers (12). Antioxidants, such as anthocyanins, flavonoids and phenolics were extracted from the grain of all three rice varieties by following the methodologies in detail (13). For antioxidant extraction, 1 g of powdered grain sample was mixed with an ethanol-citric acid solvent (80 : 20, v/v) in a 100 mL conical flask. The mixture was initially shaken on an automatic shaker for 10 min. The flask was then wrapped with aluminum foil to protect the extract from light and incubated in a hot air oven at 50 °C for 50 min. After incubation, the extract was allowed to cool to room temperature and subsequently filtered through Whatman No. 40 filter paper. The filtrate volume was made up to 50 mL with the extraction solvent. Anthocyanins and flavonoids in the extract were quantified using a UV-Vis spectrophotometer (Labman Scientific Limited, Model LMSP-UV1200) at wavelengths of 535 and 374 nm, respectively. The content of total anthocyanins and total flavonoids was determined using the proposed Eqs. 3 and 4 as described by previous researchers (14). The total anthocyanins were expressed as mg cyanidin-3-glucoside equivalents (CGE) per 100 g dry weight sample (mg CGE 100 g⁻¹ dry seed weight).

$$\text{K in soil (kg ha}^{-1}\text{)} = \frac{A \times D \times 2.24}{W} \quad \text{Eq. (1)}$$

Where, A is the concentration of K in filtrated solution used for reading in flame photometer; D is the dilution factor i.e. amount (25 mL) of 1N ammonium acetate used as an extractant, in the present study value of D was 25; W is the weight of soil and 2.24 is the conversion factor from ppm to kg ha⁻¹.

$$\text{Total K in plant (\%)} = \left\{ \frac{A \times D}{W \times 1000000} \right\} \times 100 \quad \text{Eq. (2)}$$

Where, A is the concentration of total plant K as derived from the standard curve equation, D is the total (100) dilution factor i.e. summation of 10 mL tri-acid mixture, addition of 20 mL distilled water after digestion; finally make up the volume to 100 mL. W is weight of plant sample i.e. 0.5 g, 1000000 is to express the value in parts per million (ppm). To convert the value from ppm to per cent, the same multiplied by 100.

$$\text{Total anthocyanins} = \frac{A_{535\text{nm}} \times D}{98.2} \quad \text{Eq. (3)}$$

Where, A is the reading of total anthocyanins from the spectrophotometer; D is the dilution factor and 98.2 is the empirical constant.

$$\text{Total flavonoids} = \frac{A_{374\text{nm}} \times D}{76.6} \quad \text{Eq. (4)}$$

Where, A is the reading of total flavonoids from the spectrophotometer; D is the dilution factor and 76.6 is the empirical constant.

For the estimation of total phenolics, 250 μL of the extract was mixed with 3 mL of distilled water and 250 μL of 0.2 N Folin–Ciocalteu phenol reagent, followed by stirring for 5 min. Subsequently, 250 μL of 10 % sodium carbonate (Na_2CO_3) solution and 250 μL of distilled water were added to the reaction mixture. The mixture was then incubated at 25 $^{\circ}\text{C}$ for 60 min. A gallic acid standard (10–70 $\mu\text{mol L}^{-1}$) was used for the preparation of the standard curve. After colour development, the absorbance was measured using a UV–Vis spectrophotometer (Labman Scientific Limited, Model LMSP-UV1200) at a wavelength of 761 nm. The total phenolic content was determined from the gallic acid standard curve (10–70 $\mu\text{mol L}^{-1}$) using the regression equation $y = 0.0006x + 0.0031$ ($R^2 = 0.9954$). The results were expressed as milligrams of gallic acid equivalents per 100 g dry weight (mg GAE 100 g^{-1} DW).

The experimental data for all measured parameters were analysed using analysis of variance (ANOVA) appropriate for a split-plot design in R software (version 4.2.3). Treatment effects were evaluated using the *F*-test at the 5 % level of significance. Whenever significant differences among treatments were detected, treatment means were compared using the least significant difference (LSD) test following the procedure described by Gomez and Gomez (15).

Results and Discussion

Grain yield

Variety V_3 (RNR 15048) recorded significantly superior grain yield (4.84 Mg ha^{-1}) over the two other varieties (Table 1). The least grain yield (3.19 Mg ha^{-1}) was attained with V_1 (BPT 2841). Variety V_3 , a high-yielding white rice variety, exhibited significantly higher grain yield because of its enhanced productivity potential along with efficient nutrient uptake capacity, more productive tillers, better percent grain filling with more conversion of photosynthate towards the grain (10). In contrast, V_1 produced lower yield, likely due to less tillers, reduced panicle number m^{-2} and smaller grain size. Present study showed that, variety V_2 (Kala bhat) also recorded significantly higher grain yield over V_1 .

Application of K under $K_{50-25-25}$ produced the highest grain yield (4.22 Mg ha^{-1}) and it was statistically at par with grain yield under $K_{50-50-0}$ and $K_{50-0-50}$ where the yields were 4.05 and 4.03 Mg ha^{-1} , respectively. The application of K with $K_{100-0-0}$ (recommended practice of the region) produced the lowest grain yield (3.68 Mg ha^{-1}). The interaction effect among rice varieties and K application time was found to be significant for grain yield. The higher grain yield observed under $K_{50-25-25}$ can be attributed to balanced and timely availability of K in soil solution during the key growth stages like tillering, panicle initiation and post flowering stages of the crop. Potassium helps in the transformation of energy and improves the metabolic processes of rice, which helps in the translocation of photosynthates towards reproductive parts as a result there was an increase in grain yield (16). Comparable yields under $K_{50-50-0}$ and $K_{50-0-50}$ treatments further support the effectiveness of split K application. The lowest yield under $K_{100-0-0}$ may be due to leaching losses of K in a soil with high saturated hydraulic conductivity (16.7 mm day^{-1}) along with 625 mm rainfall during the 0 to 60 DAT. The leaching loss resulted in lower degree of K availability in root zone of rice.

Total potassium in grain

Among all the varieties, significantly highest K content in grain (0.48 %) was recorded with variety V_2 (Table 1). Though K uptake rate under V_2 was lower than V_3 , but its lower mass per unit K accommodation along with 25 days more growing period, helped this variety to accumulate more amount of K in grain per unit mass at harvest. On the other hand, variety V_3 , a high yielding white rice having a greater root proliferation over the two other varieties. Greater root-soil contact helps this variety to uptake more amount of K. Potassium regulates translocation of photosynthates through the phloem (17). This caused 22 % increase in grain yield under V_3 over V_2 . The total K content in grain is an expression of K content per unit mass of the grain. Thus, increase in grain mass is the reason for the decrease value of grain K content. Due to this even with a greater uptake rate of K, V_3 landed up with lower total grain K content (0.38 %) over V_2 . Lowest leaching loss resulted in steady absorption of K by roots and this was the reason for the highest grain K content under $K_{50-25-25}$ (0.48 %). Poor uptake rate of K regulated by lower level of K in soil solution under $K_{100-0-0}$ due to its higher leaching loss in coarse textured soil was the reason for the lowest concentration of grain K under this treatment.

Table 1. Status of grain yield and antioxidant properties under the influence of potassium application times

Treatments	Grain yield, Mg ha ⁻¹	Available soil potassium, kg ha ⁻¹	Total potassium in grain, %	Antioxidants in grain, mg 100 g ⁻¹		
				Anthocyanins	Flavonoids	Phenolics
Rice varieties						
V ₁ (BPT 2841)	3.19	146.5	0.43	8.92	27.77	356.82
V ₂ (Kala bhat)	3.96	156.3	0.48	57.72	43.28	614.53
V ₃ (RNR 15048)	4.84	138.1	0.38	3.05	9.84	338.95
S. Em. ±	0.04	0.38	0.004	0.053	0.148	2.341
LSD (<i>p</i> = 0.05)	0.16	1.47	0.016	0.209	0.582	9.189
Potassium application time						
K ₁₀₀₋₀₋₀	3.68	128.5	0.38	20.37	22.83	390.02
K ₅₀₋₅₀₋₀	4.05	141.7	0.41	21.98	24.76	423.30
K ₅₀₋₀₋₅₀	4.03	154.6	0.44	24.02	28.98	450.00
K ₅₀₋₂₅₋₂₅	4.22	162.9	0.48	26.55	31.27	483.74
S. Em. ±	0.07	0.57	0.005	0.142	0.365	3.405
LSD (<i>p</i> = 0.05)	0.22	1.70	0.015	0.422	1.082	10.116
Rice varieties × Potassium application time						
S. Em. ±	0.13	1.08	0.009	0.246	0.633	5.898
LSD (<i>p</i> = 0.05)	0.39	3.38	NS	0.731	1.879	17.521

Antioxidants in rice grain

Anthocyanins

The data from the table 1 revealed that, variety V_2 being a local black rice race resulted in significantly highest anthocyanin content ($57.72 \text{ mg } 100 \text{ g}^{-1}$) in rice grain. In contrast, anthocyanins content was at its lowest level ($3.05 \text{ mg } 100 \text{ g}^{-1}$) in white rice variety V_3 . Genetic characteristics of both the varieties were responsible for such trend. Anthocyanins content among the four different application methods significantly varied from each other. Application of K in three different splits ($K_{50-25-25}$) resulted in highest anthocyanins content ($26.55 \text{ mg } 100 \text{ g}^{-1}$) in grain. This was at the lowest level ($20.37 \text{ mg } 100 \text{ g}^{-1}$) when entire recommended K (40 kg ha^{-1}) was applied as a basal in a coarse textured soil. Potassium plays a key role in enhancing secondary metabolite synthesis, including anthocyanins, by supporting enzymatic activity and improving antioxidant pathways. Results on status of anthocyanins under different K application time as presented in Table 1 established that, K plays a positive role on the status of anthocyanins in rice grain (6).

Flavonoids

The data presented in Table 1 indicated that V_2 was significantly superior for flavonoid content in grain ($43.28 \text{ mg } 100 \text{ g}^{-1}$) over the two other varieties. This is likely due to its genetic potential for flavonoid synthesis and higher plant metabolic activity due to the optimal K supply through application of K in three splits. In contrast, the lowest flavonoid content ($9.84 \text{ mg } 100 \text{ g}^{-1}$) was observed in V_3 , a high yielding white rice variety. Among the K application treatments, highest flavonoid content ($31.27 \text{ mg } 100 \text{ g}^{-1}$) was observed when K applied in three splits applications ($K_{50-25-25}$). Minimum K availability in soil or its concentration in grain under $K_{100-0-0}$ resulted in lowest level of flavonoid ($22.83 \text{ mg } 100 \text{ g}^{-1}$) in rice grain. Such results showed the role of K on flavonoid concentrations in rice grain, particularly under black rice variety (6).

Phenolics

The data listed in Table 1 indicated that variety V_2 showed significantly highest values of phenolic content ($614.53 \text{ mg } 100 \text{ g}^{-1}$) in grain over the two other varieties. As expected, V_3 recorded the lowest phenolic content in grain ($338.95 \text{ mg } 100 \text{ g}^{-1}$). The lower phenolic accumulation in V_3 a white rice variety, could be attributed to its lower phenolics synthesis capacity as compared to black rice variety like Kalabhat (V_2). Phenolics concentration under the influence of K possess similar trend to that of the anthocyanin and flavonoids. Application of K with three splits ($K_{50-25-25}$) at important pheno-phases of rice showed significantly highest phenolic content in grain ($483.74 \text{ mg } 100 \text{ g}^{-1}$) among all K application time treatments. Highest phenolic concentrations in the grain under $K_{50-25-25}$ treatment, might be due to that, at higher concentration, K influenced plant's secondary metabolite production to a greater extent, which in turn escalate accumulation of phenolics an easily soluble antioxidant (18). The lowest phenolic content ($390.02 \text{ mg } 100 \text{ g}^{-1}$) was observed when K applied in the sequence of $K_{100-0-0}$ (19).

Available soil K at harvest among all the varieties variety V_2 recorded significantly highest available soil K (156.3 kg ha^{-1}). In contrast, at harvest availability of soil K (138.1 kg ha^{-1}) was at the lowest level with V_3 (Table 1). It has already been reported that root length density of black rice is markedly lower as compared to the high yielding white rice varieties (20). This means in case of V_2 the root-soil contact per unit soil volume was minimum and the same was maximum for V_3 . This was well reflected in the status of available soil K under each rice variety. Due to its lower K uptake capacity, utilisation of K in soil solution was at a lower level under V_2 . As a result, more amount of available K remains in the soil. On the other hand, V_3 a high yielding variety have maximum root soil contact, which enhance the absorption capacity of K in root-soil interface. The highest uptake resulted in lowest amount of K left over in soil under V_3 . Splitting the application of K in three occasions ($K_{50-25-25}$) yielded significantly highest available soil K (162.9 kg ha^{-1}) among all the K application treatments. This treatment ensured a steady and well-timed supply of K to soil solution throughout the crop cycle, by minimising K losses through leaching. In contrast $K_{100-0-0}$ treatment showed lowest available soil K (128.5 kg ha^{-1}). Split applications of K have been reported to improve K use efficiency and yield in rice (10), while leaching in coarse-textured soils contributes to lower K use efficiency, which can be mitigated through split applications (19).

Relationship between available soil or total plant K with different antioxidants: The degree of influence of available soil K as well as total grain K content on all three antioxidants have been assessed by computing the coefficient of determination (R^2) values on the basis of regression equation of the trend lines generated on the relationships in between soil / grain K with the three antioxidants mentioned earlier. Based on the value of R^2 the relationships are categorised as: very strong ($R^2 \geq 0.9$); strong (R^2 in between 0.8 to 0.89) and moderately strong ($R^2 \leq 0.79$). All 18 R^2 values represent the soil or grain K relationships with the antioxidants under V_1 (high yielding black), V_2 (black) and V_3 (white rice) rice varieties are presented in Table 2. In case of rice varieties, based on R^2 values the strength of relationships were in the order of $V_2 > V_1 > V_3$. Interestingly, influence of available soil K on antioxidants found stronger than the influence of grain K content on antioxidants. Unlike nitrogen, grain is not the main sink for K. Rather K remains in the straw to perform activities against various abiotic and biotic stresses that rice crop faces at the reproductive phase. This was the reason for greater influence of available soil K than that of the grain K content. As it is difficult to present all the figures showing the relationships, six best relationships covering three each from soils and grains are presented here.

As per Fig. 1, available soil K very strongly influenced the concentration of grain anthocyanins. Here, 94 % variation in anthocyanins levels can be attributed to difference in available soil K. A strong positive linear relationship was observed between total K content in grain and anthocyanin concentration, as illustrated in Fig. 2. The high coefficient of determination ($R^2 = 0.89$) indicates that 89 % of the variation in anthocyanin levels can be attributed to

Table 2. Strength of coefficient of determination (R^2) expressing the relationship in between soil or plant potassium with different antioxidants

Rice varieties	Potassium	Anthocyanins	Flavonoids	Phenolics
			R^2	
BPT 2841 (V_1)	Available soil potassium	0.94	0.85	0.94
	Total grain potassium	0.71	0.74	0.86
Kala bhat (V_2)	Available soil potassium	0.93	0.93	0.93
	Total grain potassium	0.89	0.81	0.85
RNR 15048 (V_3)	Available soil potassium	0.73	0.90	0.93
	Total grain potassium	0.87	0.74	0.84

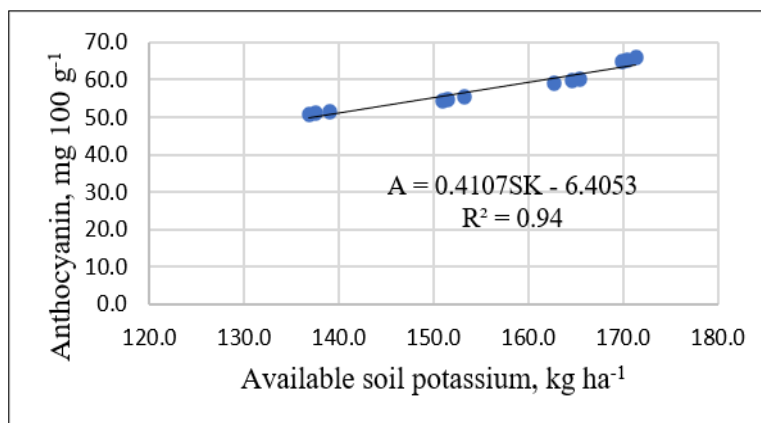


Fig. 1. Influence of available soil potassium on status of grain's anthocyanins.

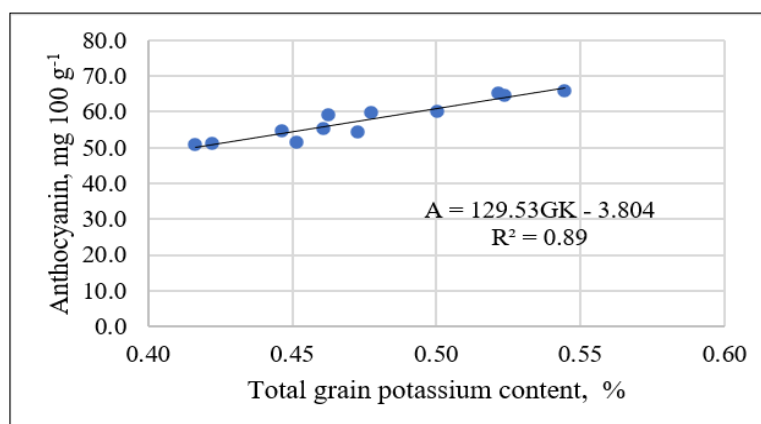


Fig. 2. Influence of total grain potassium content on status of grain's anthocyanins.

differences in grain K content. This implies that higher K accumulation in soil as well as in grain may play a significant role in promoting anthocyanin biosynthesis in black rice variety (V_2). The non-pigmented variety V_3 exhibited comparatively lower anthocyanin concentrations across all K levels, reflecting its genetic limitation in anthocyanin biosynthesis. This denotes that while K accumulation is positively associated with anthocyanin content, the extent of this effect is also influenced by the inherent pigmentation potential of the rice variety. Like anthocyanins, concentration of flavonoids is also very strongly ($R^2 = 0.93$) influenced by the availability of K in soil solution (Fig. 3). However, 81 % of the variation in flavonoids content can be explained by differences in grain K content (Fig. 4). This indicates that both soil and grain K contribute significantly to enhanced flavonoid synthesis. However, the response may also vary depending on the genetic makeup of the rice variety, with pigmented variety (V_2) likely exhibiting higher flavonoid

concentrations than non-pigmented ones such as V_3 . Like anthocyanins and flavonoids, phenolics concentration in grain also very strongly dependent ($R^2 = 0.93$) on available soil K (Fig. 5). A strong positive relationship was observed between total K concentration in the grain and the grain phenolic content (Fig. 6). The coefficient of determination ($R^2 = 0.85$) indicates that 85 % of the variability in phenolics content is associated with differences in total K levels in grain. This relationship suggests that higher K accumulation in rice grains significantly enhances the synthesis or retention of grain phenolic compounds.

Conclusion

Based on the experimental results, it can be concluded that the variety Kalabhat (V_2) recorded the highest available soil potassium (K), total K content and antioxidant properties such as

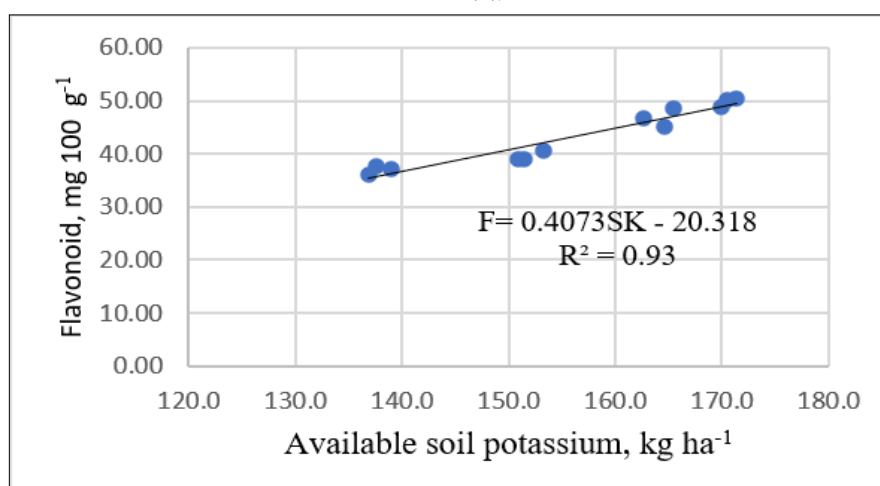


Fig. 3. Influence of available soil potassium on status of grain's flavonoids.

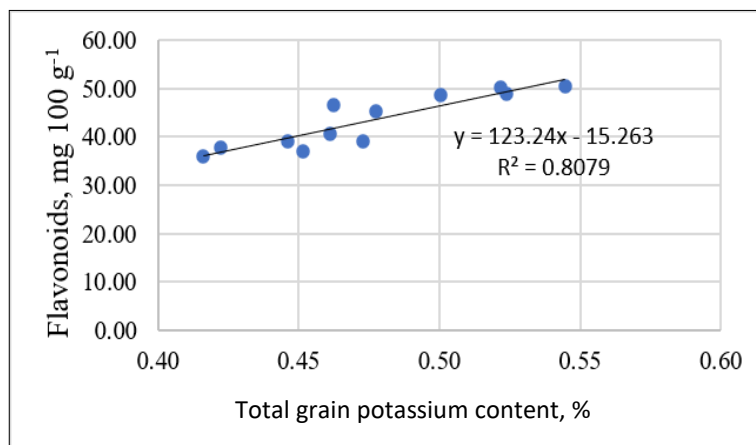


Fig. 4. Influence of total grain potassium content on status of grain's flavonoids

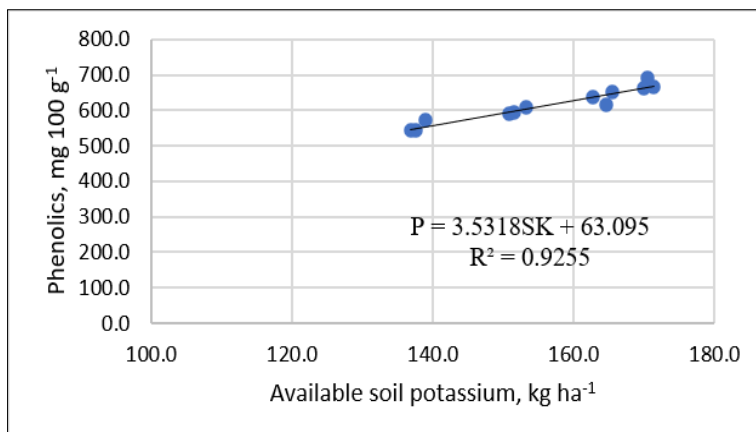


Fig. 5. Influence of available soil potassium on status of grain's phenolics.

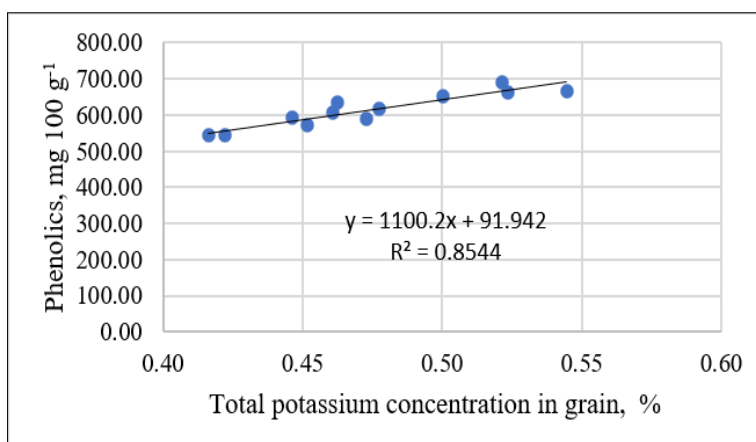


Fig. 6. Influence of total grain potassium content on status of grain's phenolics.

anthocyanin, flavonoid and phenolic. It was found that RNR 15048 (V_3) produced maximum yield. In case of K application time, $K_{60-25-25}$ i.e., 50 % applied at basal, 25 % applied at active tillering and rest 25 % applied at panicle initiation resulted highest available soil K, total K content in grains, grain yield and status of soluble antioxidant. Therefore, under coarse-textured soils with high K leaching potential, farmers cultivating black rice may adopt this three-split K application schedule to enhance both productivity and grain nutritional quality.

Future research should validate this K scheduling strategy across different agro-climatic regions, soil types and black rice genotypes and investigate the physiological and biochemical mechanisms governing K-mediated antioxidant accumulation under diverse environmental conditions.

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Authors' contributions

VN contributed to the original research, field and laboratory investigations, experimental design, research administration and overall supervision. TS contributed to conceptualisation, co-supervision and preparation of the original draft. SS contributed to antioxidant study supervision and technical guidance. GKD

contributed to data analysis and statistical interpretation. SM contributed to field and laboratory investigations. SR contributed to proofreading. AK, SS and SM contributed to the final review of the manuscript. All authors have read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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