



Soil Applied Potassium Combined with Foliar Application of Macro and Micronutrients Improved Yield and Economic Returns of Cotton (*Gossypium hirsutum* L.)

Hakan Ünal Ağaç¹ · Hasan Haliloğlu¹

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Abstract

Improper or inadequate mineral nutrition is a major issue in cotton (*Gossypium hirsutum* L.) production globally. Therefore, the development of balanced fertilization strategies is essential for sustainable cotton production. This study assessed the impacts of soil-applied potassium (K) doses ($K_0=0$, $K_{70}=70$, $K_{140}=140$, and $K_{210}=210$ kg ha⁻¹) combined with water (F_0 =control) foliar-applied humic acid ($F_1=150$ g humic acid in 100 L water), micronutrients (F_2 = (250 g of micronutrient mixture containing 7% iron (Fe), 7% zinc (Zn), 1% boron (B), 5% manganese (Mn), 0.05% molybdenum (Mo) and 1% copper (Cu) in 100 L water), and macro+micronutrients ($F_3=500$ g urea+500 g potassium sulfate+100 g zinc sulfate+100 g F_2 in 100 L water) on yield-related and fiber quality traits, and ginning outturn of cotton during 2020 and 2021. Frequently cultivated genotype ‘Fiona’ was used in the study. The K was applied at the time of sowing, whereas foliar treatments were applied at square initiation, flowering initiation, and peak flowering. The individual and interactive effects of soil-applied K and foliar applied nutrients significantly altered yield and related traits, whereas fiber quality traits remained unaffected during both years. Overall $K_{210} \times F_3$ interaction resulted in the highest values of yield-related traits and seed cotton yield. The highest seed cotton yield (6428 and 6185 kg ha⁻¹ during 2020 and 2021, respectively) was recorded for $K_{210} \times F_3$ interaction. Similarly, $K_{210} \times F_3$ interaction resulted in the highest net returns (709 and 496 US\$ ha⁻¹ during 2020 and 2021, respectively) and benefit: cost ratio (1.90 and 1.50 during 2020 and 2021, respectively). Overall, the highest seed cotton yield and economic returns were recorded for $K_{210} \times F_3$ interaction. Therefore, it is recommended to apply 210 kg ha⁻¹ K followed by foliar application of macro+micronutrients for higher yield and economic returns.

Keywords Cotton · Economic analysis · Foliar fertilizer · Humic acid · Micronutrients · Sustainable production

1 Introduction

Cotton (*Gossypium hirsutum* L.) remains an essential element of the global textile industry, significantly impacting the economy, society, and environment. It is a crucial fiber in the worldwide production of yarn, fabric, and clothing owing to its widespread cultivation (Khan et al. 2020). The significance and demand for cotton are progressively increasing due to the rapid growth of the global population

and the corresponding rise in cotton consumption across diverse industries (Han et al. 2024). The growing demand for cotton, driven by evolving living standards, has heightened interest in the textile industry (Sadhna et al. 2024). Cotton is principal raw material for the textile industry; therefore, gaining significant importance in Türkiye like the rest of the world (Gürsoy and Akın 2024). Cotton is a vital export commodity for numerous countries and plays a significant role in supporting agricultural employment (Kabish et al. 2024).

Türkiye is among the few countries in the world capable of carrying out all stages of production in the textile and apparel industries (Basal et al. 2019). Türkiye effectively pulls this advantage within the textile and apparel industries (Tokel et al. 2022). The rising global interest in fibers

✉ Hasan Haliloğlu
haliloglu@harran.edu.tr

¹ Faculty of Agriculture, Department of Field Crops,
University of Harran, Osmanbey Campus Şanlıurfa, Türkiye

is concurrently increasing the need for cotton (Han et al. 2024). Currently, cotton fibers serve as raw materials in several sectors, including textiles, tulle, quilts, apparel, carpets, yarn, twine, smokeless gunpowder, varnish, polish, synthetic leather, and cellulose (Baydar et al. 2015; Khan et al. 2020). The oil content of cotton seeds (17–24%) is progressively enhancing its significance in the oil business (Kebede 2024). The residual cottonseed meal has 40–43% protein, 20–22% nitrogen-free extract, and 5–8% oil, making it valued animal feed (Kebede 2024).

Cotton plants require a continuous supply of nutrients throughout vegetative (leaf, stem, and branch development) and reproductive (flowering and fruit formation) growth stages due to indeterminate growth characteristics (Rehman and Farooq 2019). Consequently, adequate nutrients supply is essential throughout the growing period for higher productivity and superior fiber quality (Constable and Bange 2015; Rochester et al. 2012). Fiber yield and quality depend upon nutrient availability and environmental conditions during the growth season (Bradov and Davidonis 2010). Nitrogen (N), phosphorus (P), and potassium (K) are the major nutrients required by cotton plants. Cotton plants extract 6–7 kg N, 1.9–2.5 kg P, 6–8 kg K, and 1.2–2.0 kg of sulfur (S) from the soil for producing 100 kg seed cotton (Pettigrew 2008). Cotton is recognized for its significant requirements for K, positioning it as an essential nutrient for optimal growth (Oosterhuis et al. 2013). Potassium regulates several biochemical processes associated with plant development and physiology, enzyme activation, and protein synthesis in cotton (Hasanuzzaman et al. 2018). It is necessary for plant water relations, development of new tissues, photosynthetic processes, water equilibrium, transport of carbohydrates and sugars, and different metabolic activities (Coker et al. 2009). Deficiency symptoms in leaves create yellowish patches that transition to brown between the veins and along the leaf margins, resulting in desiccation. This may lead to accelerated aging (Reed 2019).

Cotton needs considerable quantities of K for optimal plant growth and fiber development (Singh et al. 2024; Vidal et al. 2017). Cotton exhibits increased sensitivity to low K availability than other crops and often develop deficiency symptoms (Denton et al. 2023). The deficiency may arise from insufficient K levels in the soil, K-fixation within the soil, or increased K requirements of modern cotton cultivars (Denton et al. 2023). The K deficiency significantly reduces the number of bolls per plant and boll weight (Hu et al. 2016), leading to considerable yield reduction (Li et al. 2012). Nevertheless, lint percentage remains unaffected by K deficiency (Gormus and Yucel 2002). Fiber quality, i.e., fiber strength (Yang et al. 2016), fiber length (Girma et al. 2007), fiber maturity, and micronaire (Pettigrew 2008) are negatively impacted by K deficiency. The K deficiency may

decrease cotton yield by ~20% through reduction in boll quantity and boll weight (Shao et al. 2024). Nevertheless, K application can enhance plant growth and physiology and improve drought tolerance (Oosterhuis et al. 2013). Despite adequate K reserves in soils, a significant proportion of arable agricultural lands exhibits K-deficiency (Mengel et al. 2001). The K-deficiency is mostly observed in sandy, waterlogged, saline, acidic, and organically structured soils (Singh 2022). The judicious use of K is crucial for maximizing plant development, seed cotton yield, and fiber quality (Singh et al. 2024; VIDAL et al. 2017).

The N and P are often prioritized in cotton nutrition; however, K, sulfur (S), and other micronutrients are mostly neglected (Xiao and Yin 2019). Micronutrients are essential for improving cotton yield and fiber quality by improving nutrient absorption efficiency, stress resilience, and fiber development (Ahmed et al. 2020). Boron (B) is essential for cell wall synthesis and elongation (Matoh 2001); zinc (Zn) is involved in enzyme activity, protein synthesis, and root growth (Mousavi 2011); iron (Fe) is critical for chlorophyll synthesis and photosynthesis (Miller et al. 1995); manganese (Mn) serves as a cofactor for enzymes involved in stress response (Schmidt and Husted 2019); and copper (Cu) contributes to lignin deposition, enhancing fiber strength and minimizing breakage during processing (Xiao et al. 2022). However, micronutrients are often ignored in cotton nutrition. Foliar application of micronutrients with fertilizers such as P and K during blooming and boll development has been proved useful in enhancing nutrient utilization in cotton (Abbas et al. 2021). Foliar application facilitates quick absorption of plant nutrients, enabling the early improvement of deficiencies (Niu et al. 2021). Foliar application often requires a reduced quantity of fertilizer in comparison to soil application (Fageria et al. 2009). Therefore, N, P, and K, and micronutrients could be applied by foliar fertilization under deficit conditions of these nutrients (Oosterhuis 2001).

Humic acid is a constituent of humus derived by the breakdown of organic materials in the soil (Hayes and Swift 2020). It comprises complex molecules that enhance soil structure, nutrient availability, and water retention ability. Humic acid enhances the efficiency of nutrient absorption in cotton plants, i.e., N, P and K (Ullah et al. 2020). Humic acid may demonstrate stress-mitigating effects, including heat, salinity, and pH levels. The primary functional groups of humic compounds include carboxyl, phenolic hydroxyl, alcoholic hydroxyl, ketone, and quinone. Reports indicate that humic acid improved plant characteristics under saline environments (Dell'Amico et al. 1994; Onder et al. 2005). Humic acid may be foliar applied to cotton plants for direct absorption, especially during the blooming and boll development phases.

Soil-applied K is essential for enhancing cotton yield and boll development, while foliar treatments of macro and micronutrients facilitate quick nutrient absorption and can enhance plant health and fiber quality. A comprehensive strategy that combines various techniques can markedly improve the efficiency and sustainability of cotton production. Hence, it is crucial to cultivate cotton with balanced nutrition to improve yield and fiber quality. This study investigated the effect of soil-applied K combined with foliar applied micro and macronutrients combinations to improve yield and fiber quality. It was hypothesized that combined application of K and macro+micronutrients will significantly improve yield and fiber quality of cotton.

2 Materials and Methods

2.1 Experimental Site

This study was conducted in the Kılıçlı village, Harran district, Şanlıurfa province, Türkiye during 2020 and 2021. The Harran Plain (experimental site) has been formed by mudflows originating from the Tektek, Fatik, and Urfa Mountains, which surround the plain to the east, west, and north, respectively. The soil is of alluvial origin, characterized by a flat or slightly inclined topography (Dinç et al. 1988).

2.2 Soil Properties

Soil samples (0–30 cm) were collected from 3 random places in the experimental site and analyzed to determine soil properties. Soil analysis indicated that the experimental site had slightly alkaline pH (7.73) and a moderate electrical conductivity (0.88 dS m^{-1}), indicating non-saline conditions. The lime concentration was notably high (25.8%) which could impact nutritional availability. The total P (phosphorus) and K (potassium) were 634 kg ha^{-1} and 1254 kg ha^{-1} , respectively, indicating adequate macronutrient availability. The organic matter content was low (1.36%), potentially affecting soil fertility and microbial activity (Table 1).

2.3 Weather

The average annual temperature ranged from 17.1°C to 34.2°C during the cotton growing season in 2020 (Fig. 1a), and from 19.1°C to 33.8°C in 2021. The highest temperature (45.3°C) was recorded in July 2020 and 44.4°C in July

2021. The lowest temperatures were 4.8°C in March 2020 and 5.5°C in March 2021 (Fig. 1b). The long-term average weather data is presented in Fig. 1c.

2.4 Treatments

The experiment consisted of two factors, i.e., soil applied K and foliar applied nutrients in different doses. Four K levels, i.e., K_0 =control, $K_{70}=70 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, $K_{140}=140 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, and $K_{210}=210 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$ were included in the study. Similarly, foliar applied nutrients were, F_0 =control, F_1 =humic acid (150 g in 100 L water), F_2 =micronutrient combination [(Fe (7%), Zn (7%), B (1%), Mn (5%), Mo (0.05%), Cu (1%)] (250 g in 100 L water), and F_3 =macronutrients [500 g urea (46% N)+500 g K_2SO_4 +100 g zinc sulfate]+micronutrients (100 g F_2) combination in 100 L water. The experiment was conducted according to a randomized block design with split plots and three replications. The K levels served as the primary plots, whereas the foliar applied nutrients were randomized in sub-plots.

Foliar treatments were prepared according to the specified doses using 400 L of water per hectare. The nutrient solutions were applied to the foliage in the evening at three growth stages (i.e., square initiation, flowering initiation, and peak flowering) using a pre-calibrated backpack sprayer. Only water was sprayed to the control treatment.

2.5 Soil Preparation

Deep plowing was done at the experimental site during fall, and in April, a medium-tillage (25 cm) was performed using a cultivator. Afterward, clods were broken up with a disc harrow, and a roller was used to prepare a fine seedbed. Seeds were sown on May 20 during both years using a seed drill with an inter-row spacing of 75 cm and intra-row spacing of 8–10 cm. A 3-meter gap was maintained between plots and replications.

Each experimental unit consisted of 10-m long 6 rows. At sowing, 100 kg of pure N and P per hectare was applied using 20-20-0 compound fertilizer. Afterwards 140 kg ha^{-1} of pure N (46% urea) was applied with first and second irrigations. Two cultivations were performed in June to control weeds during 2020. However, two manual hoeing were done in June and July during 2021 for weed control. Prior to sowing, Pendimethalin (4.50 kg ha^{-1} , 3000 ml ha^{-1}) was applied to the soil to control both narrow and broadleaf weeds.

Table 1 Soil properties of the experimental site

Depth	pH	EC ds m^{-1}	Lime (%)	Total P (kg ha^{-1})	Total K (kg ha^{-1})	Organic matter (%)
0–30 cm	7.73	0.88	25.8	634	1254	1.36

EC=electrical conductivity, P=phosphorus, K=potassium

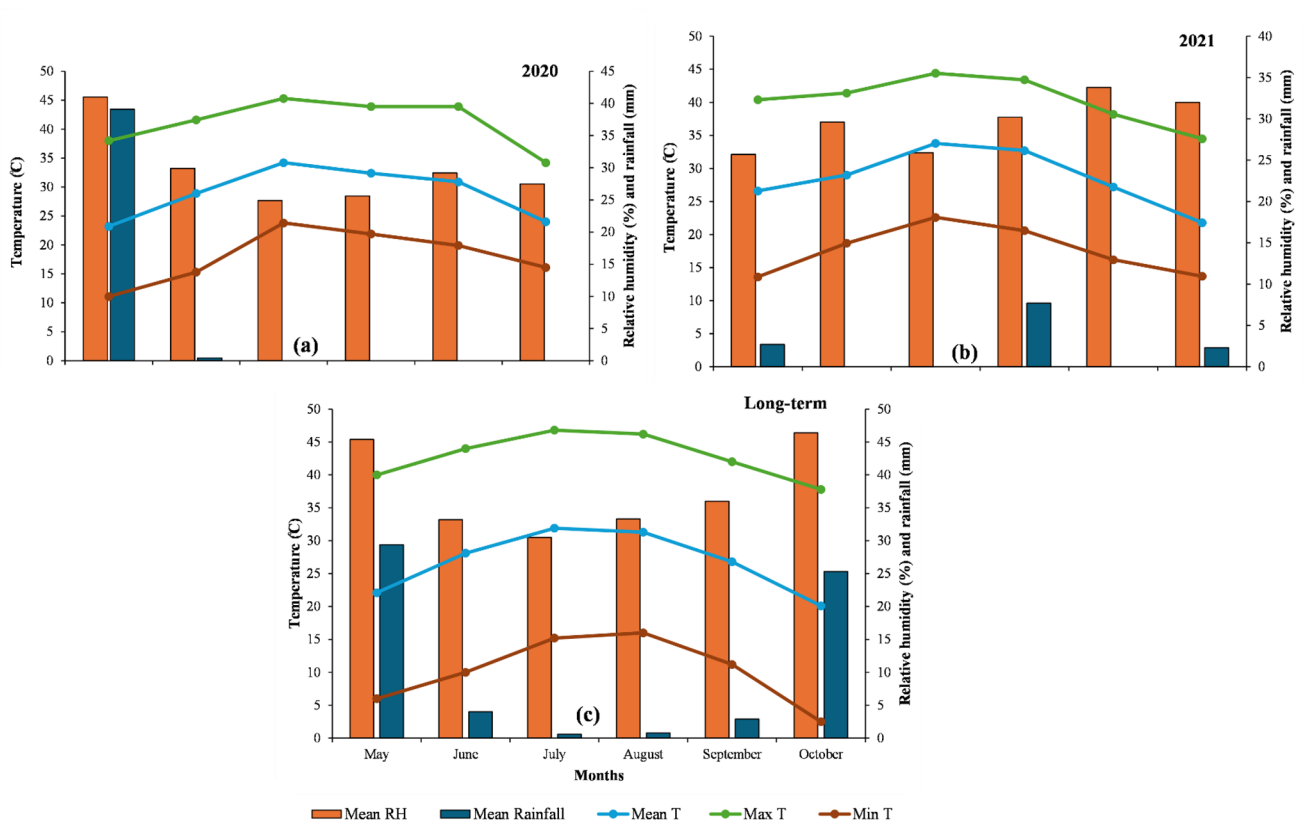


Fig. 1 Weather data of the experimental site during cotton growing seasons of 2020 (a) and 2021 (b) along with long-term average (c). Mean RH=mean relative humidity, Mean T=mean temperature, Min T=minimum temperature, and Max T=maximum temperature

Approximately 15 days after the last irrigation date, 1750 ml ha⁻¹ of defoliant (ethephon+cyclanilide) and 600 ml ha⁻¹ of boll opener (thidiazuron+diuron) were applied during both years. Depending on the air temperature 10–12 days after the application of defoliant and boll opener, 12 m² (8 × 1.5) area excluding 1 m from both edges was harvested manually (14 and 23 October during 2020 and 2021, respectively). The harvested cotton bolls were weighed to record seed cotton yield.

2.6 Data Collection

Seed cotton yield (kg ha⁻¹), number of monopodial and sympodial branches (plant⁻¹), the number of bolls (plant⁻¹), boll seed cotton weight (g), and ginning outturn (%) were determined according to standard methods (Worley et al. 1976). Fiber quality traits, i.e., fiber length, fiber fineness (micronaire), and fiber strength (g tex⁻¹) were assessed using the High-Volume Instrument (HVI 1000 A system) using standard protocols (Delhom et al. 2018). Fiber length was assessed using an optical scanning method that aligns and combs the fibers to quantify the longest 50% of the

fiber population. The fineness was evaluated by an airflow method that measures the resistance of air flowing through a compressed fiber sample. The strength was assessed by securing a fiber bundle and applying tensile force till rupture. All measurements were performed under regulated atmospheric conditions (65% ± 2% relative humidity and 21 °C ± 1 °C) to guarantee precision and consistency.

2.7 Statistical Analysis

The data relating to yield and fiber related traits were analyzed by two-way analysis of variance (ANOVA) (Steel et al. 1997) using JMP 16 statistical software (Jones and Sall 2011). The data were checked for normality first, which denoted a normal distribution. Hence, originally collected data were used in statistical analysis. Furthermore, the differences among years were tested using paired t test, which indicated significant differences among years. Therefore, data for each year were analyzed and presented separately. Treatment means were grouped by using Tukey post-hoc test where ANOVA denoted significant differences among treatments.

2.8 Economic Analysis

An economic analysis was conducted to determine the economic benefits of soil applied K combined with foliar applied nutrients (Byerlee and Halter 1974). The overall production cost was calculated by aggregating all fixed and variable input expenses. The fixed costs included land preparation, seeds, fertilizers, pesticides, irrigation, labor, and harvesting costs. Similarly, variable cost consisted of expenses incurred on soil-applied K and foliar applied nutrients. Yield data from various treatments were utilized to compute gross revenue by multiplying the market price of cotton per kilogram by the yield. Net income was derived by deducting total production expenses from gross revenue. The benefit-cost ratio was calculated by dividing gross revenue by total expenditure.

3 Results

The analysis of variance indicated that potassium doses (K) and foliar fertilizers (FF) significantly ($P < 0.05$) influenced most yield traits, i.e., number of monopodial and sympodial branches, number of bolls per plant, boll weight, and seed cotton yield during 2020 and 2021. The $K \times FF$ interaction was significant for the number of monopodial and sympodial branches, the number of bolls per plant, and seed cotton yield in both years (Table 2). Nonetheless, K, FF, and their interaction remained non-significant ($P > 0.05$) for fiber quality traits, i.e., fiber length, fiber fineness, and fiber strength. Furthermore, the ginning outturn in 2021 was significantly affected by K (Table 2).

3.1 Yield and Related Traits

The lowest (1.10) and the highest (1.29) number of monopodial branches were recorded for K_{70} and K_0 doses, respectively during 2020, whereas K_{210} and K_0 resulted in the lowest (1.21) and the highest (1.39) number of monopodial branches during 2021 (Fig. 2a). Similarly, F_0 and F_2 fertilization treatments resulted in the lowest (1.14) and the highest (1.31) number of monopodial branches, respectively during 2020, while F_1 and F_2 resulted in the lowest (1.25) and the highest (1.38) number of monopodial branches during 2021 (Fig. 2f). The $K \times FF$ treatment interactions indicated that $K_{70} \times F_2$ produced the highest number of monopodial branches (1.43–1.67). The average number of monopodial branches in 2020 was lower than in 2021 across all treatments (Table 3).

The lowest (12.88 and 9.13) and the highest (14.11 and 10.62) number of sympodial branches were recorded for K_0 and K_{140} doses, respectively during both years (Fig. 2b).

Similarly, F_0 and F_1 foliar fertilization treatments resulted in the lowest (12.84) and the highest (14.07) number of sympodial branches, respectively during 2020, while F_0 and F_2 resulted in the lowest (9.60) and the highest (10.36) number of sympodial branches during 2021 (Fig. 2g). Regarding interaction, $K_{140} \times F_2$ interaction produced the greatest number of sympodial branches (15.17–11.33). The average number of sympodial branches in 2020 was higher than in 2021 across all treatments (Table 3).

The lowest (10.91) and the highest (12.51) number of bolls were recorded for K_0 and K_{140} , respectively during 2020. However, K_0 and K_{70} resulted in the lowest (8.39) and the highest (9.06) number of bolls, respectively during 2021 (Fig. 2c). Among fertilization treatments, F_0 and F_3 produced the lowest (11.14) and the highest (12.42) number of bolls per plant, respectively during 2020. Nevertheless, F_0 and F_2 resulted in the lowest (8.62) and the highest (9.05) number of bolls per plant during 2021, respectively (Fig. 2h). The $K_{70} \times F_2$ interaction resulted in the highest number of bolls per plant (13.46 to 9.50) across both years. The average number of bolls recorded during 2020 was greater than 2021 across all treatments. The increased number of bolls in 2020 positively influenced seed cotton yield (Table 3).

The lowest (5.27 and 4.64 g) and the highest (6.03 and 5.00 g) boll weight was noted for K_0 and K_{210} , respectively during both years (Fig. 2d). Similarly, F_1 and F_3 resulted in the lowest (5.42 g) and the highest (6.14 g) boll weight during 2020, whereas F_0 and F_3 treatments produced the lowest (4.65 g) and the highest (4.94 g) boll weight during 2021 (Fig. 2i). Regarding interactive effects, $K_{210} \times F_3$ produced the highest boll weight during both years (Table 3).

The lowest (5025.9 and 4288.3 kg ha⁻¹ during 2020 and 2021, respectively) and the highest (6089.5 and 5128.2 kg ha⁻¹) seed cotton yield was recorded K_0 and K_{210} treatments respectively (Fig. 2e). Similarly, F_0 and F_2 treatments resulted in the lowest (5385.8 and 4403.0 kg ha⁻¹) and the highest (5944.4 and 5083.3 kg ha⁻¹) seed cotton yield (Fig. 2j). Regardless of the years $K_{210} \times F_3$ (6428.9–6185.5 kg ha⁻¹) interaction resulted in the highest seed cotton yield. Overall, higher seed cotton yield was recorded during 2020 than 2021 (Table 3).

3.2 Ginning Outturn and Fiber Quality Traits

The ginning outturn varied between 44.01% and 44.60% during 2020 and 42.30–43.58% during 2021 under different K doses (Fig. 3d). The K doses $\times$ FF interaction remained non-significant in this regard (Table 4). All other fiber quality traits remained unaffected by individual (Fig. 3a–h) and interactive effects (Table 4) of K doses and foliar fertilization treatments during both years.

Table 2 Analysis of variance for different yield and fiber quality traits of cotton grown with different potassium doses and foliar fertilizer treatments

		2020				2021			
Source	DF	SS	MS	F value	P value	SS	MS	F value	P value
Number of monopodial branches									
K	3	0.22	0.07	36.89	<0.0001	0.25	0.08	24.09	<0.0001
FF	3	0.21	0.07	34.82	<0.0001	0.11	0.04	10.38	<0.0001
K × F	9	0.91	0.10	50.26	<0.0001	1.36	0.15	44.28	<0.0001
Number of sympodial branches									
K	3	10.78	3.59	14.53	<0.0001	15.77	5.26	23.26	<0.0001
FF	3	16.23	5.41	21.88	<0.0001	5.20	1.73	7.67	0.001
K × F	9	2.34	0.26	1.05	0.422	5.72	0.64	2.81	0.015
Number of bolls per plant									
K	3	18.02	6.01	18.19	<0.0001	3.52	1.17	22.37	<0.0001
FF	3	11.16	3.72	11.26	<0.0001	1.19	0.40	7.54	0.001
K × F	9	16.70	1.86	5.62	0.000	4.45	0.49	9.45	<0.0001
Boll weight									
K	3	3.45	1.15	14.29	<0.0001	0.87	0.29	12.20	<0.0001
FF	3	4.03	1.34	16.68	<0.0001	0.52	0.17	7.33	0.001
K × F	9	1.46	0.16	2.01	0.071	0.08	0.01	0.37	0.939
Seed cotton yield									
K	3	79,098	26,366	56.97	<0.0001	63,054	21,018	54.64	<0.0001
FF	3	20,598	6866	14.83	<0.0001	43,259	14,419	37.49	<0.0001
K × F	9	9207	1023	2.21	0.048	41,028	4558	11.85	<0.0001
Ginning outturn (%)									
K	3	2.18	0.73	2.72	0.061	12.23	4.08	26.76	<0.0001
FF	3	0.74	0.25	0.93	0.439	0.09	0.03	0.19	0.901
K × F	9	2.53	0.28	1.05	0.423	0.26	0.03	0.19	0.994
Fiber length (mm)									
K	3	4.34	1.45	1.95	0.142	6.83	2.28	0.75	0.528
FF	3	3.60	1.20	1.62	0.205	3.69	1.23	0.41	0.748
K × F	9	4.57	0.51	0.68	0.718	21.68	2.41	0.80	0.620
Fiber fineness (micronaire)									
K	3	0.01	0.00	0.30	0.825	0.08	0.03	0.37	0.773
FF	3	0.02	0.01	0.85	0.479	0.13	0.04	0.62	0.607
K × F	9	0.07	0.01	1.03	0.441	0.19	0.02	0.31	0.964
Fiber strength (g tex ⁻¹)									
K	3	29.11	9.70	44.47	0.801	57.34	19.11	4.39	0.801
FF	3	0.16	0.05	0.24	0.866	8.94	2.98	0.68	0.568
K × F	9	0.91	0.10	0.47	0.887	15.72	1.75	0.40	0.925

Source=source of variation, K=potassium doses, FF=foliar fertilizer treatments, DF=degrees of freedom, SS=sum of squares, MS=mean squares, the bold values in the P value column indicate that the relevant individual or interactive effects are significant ($p < 0.05$)

3.3 Economic Returns

Interactive effect of soil applied potassium and foliar fertilization treatments significantly influenced economic returns and benefit: cost ratio (BCR). The $K_{210} \times F_3$ was the most effective treatment resulting in the greatest gross and net revenues, along with the highest BCR in both years. A significant reduction in profitability (net income and BCR) was seen in the 2021 season for most treatments attributed to decreased yield. Treatments without K application (K_0) were less lucrative, particularly in the 2021 season,

demonstrating that K is essential for improving cotton production and economic returns (Table 5).

The highest net income in 2020 was noted for $K_{210} \times F_3$ (629 US\$ ha⁻¹), followed by $K_{210} \times F_2$ (622 US\$ ha⁻¹). In 2021, $K_{210} \times F_3$ had the greatest net income of 603 US\$ ha⁻¹, but a decrease from the prior year. Treatments without K application (K_0) exhibited reduced net incomes, especially in 2021, when the majority of K_0 treatments yielded net incomes < 300 US\$ ha⁻¹ (Table 5). The highest BCR of 1.90 was recorded for $K_{210} \times F_3$ and $K_{210} \times F_2$ during 2020. The lowest BCR in 2020 was 1.60 for $K_0 \times F_0$. In 2021, the highest BCR was recorded for $K_{210} \times F_3$ (1.50) (Table 5).

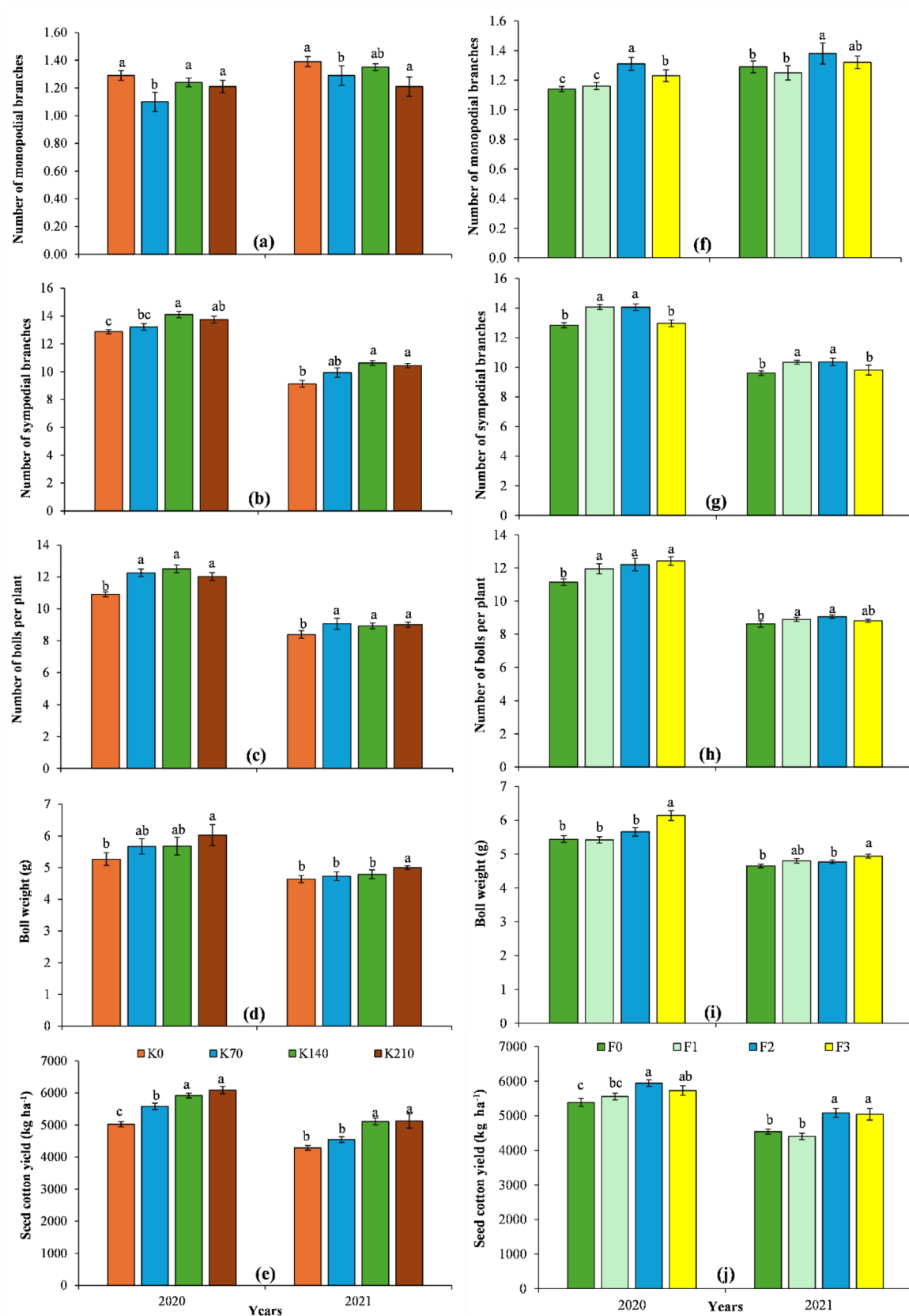


Fig. 2 The influence of different potassium doses (a–e) and foliar fertilization treatments (f–j) on the number of monopodial branches, the number of sympodial branches, the number of bolls per plant, boll weight and seed cotton yield. The error bars are standard errors of the means ($n=3$). The means with different letters are significantly different from each other. K_0 =control, $K_{70}=70 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, $K_{140}=140 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, and $K_{210}=210 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, F_0 =control, F_1 =humic acid (150 g in 100 L water), F_2 =micro active combination [Fe (7%), Zn (7%), B (1%), Mn (5%), Mo (0.05%), Cu (1%)] (250 g in 100 L water), and F_3 =specially designed nutrient solution (500 g urea (46% N)+500 g K_2SO_4 +100 g zinc sulfate+100 g micro active combination in 100 L water)

4 Discussion

The results indicated that soil-applied K and foliar fertilizer treatments significantly impacted essential cotton yield components, i.e., number of monopodial and

sympodial branches, bolls per plant, boll weight, and seed cotton yield, whereas fiber quality traits were unaffected. The notable interaction between K and foliar fertilizer treatments for yield attributes indicates that a synergistic application technique improves cotton productivity. Seed cotton yield is a complex characteristic, greatly impacted by genotype $\times$ environment interactions, and is enhanced by the increased growth of flowers, and improved number of leaves, branches, roots, and fruits (Rehman and Farooq 2019). The $K_{210} \times F_3$ interaction resulted in the highest seed cotton yield in both years, demonstrating that 210 kg K ha^{-1} , combined with foliar application of macro+micronutrients effectively satisfies the nutrient requirements of cotton. Potassium improves photosynthesis and assimilate distribution, hence facilitating boll development and seed formation

Table 3 Interactive effect of different potassium doses and foliar fertilization treatments on yield and related traits of cotton

Interactions	Monopodial branches (plant^{-1})		Sympodial branches (plant^{-1})		Number of bolls (plant^{-1})	
	2020	2021	2020	2021	2020	2021
$K_0 \times F_0$	$1.17 \pm 0.12 \text{ cde}^{\#}$	$1.33 \pm 0.66 \text{ def}^{\#}$	$12.33 \pm 1.0^{\text{ns}}$	$9.03 \pm 1.7 \text{ ef}^{\#}$	$10.43 \pm 1.3 \text{ d}$	$7.82 \pm 0.6 \text{ f}^{\#}$
$K_0 \times F_1$	$1.23 \pm 0.09 \text{ cd}$	$1.45 \pm 0.27 \text{ b-e}$	13.43 ± 2.4	$9.79 \pm 1.4 \text{ cde}$	$10.47 \pm 4.4 \text{ d}$	$8.73 \pm 0.8 \text{ b-e}$
$K_0 \times F_2$	$1.47 \pm 0.20 \text{ a}$	$1.53 \pm 0.60 \text{ abc}$	13.23 ± 0.1	$9.52 \pm 1.6 \text{ de}$	$11.03 \pm 3.0 \text{ cd}$	$8.69 \pm 0.3 \text{ cde}$
$K_0 \times F_3$	$1.28 \pm 0.31 \text{ bc}$	$1.28 \pm 0.30 \text{ efg}$	12.51 ± 1.1	$8.19 \pm 0.6 \text{ f}$	$11.70 \pm 2.5 \text{ a-d}$	$8.30 \pm 0.9 \text{ ef}$
$K_{70} \times F_0$	$1.07 \pm 0.24 \text{ e}$	$1.27 \pm 0.19 \text{ efg}$	12.42 ± 1.9	$9.64 \pm 3.0 \text{ cde}$	$11.70 \pm 2.8 \text{ a-d}$	$9.40 \pm 2.1 \text{ ab}$
$K_{70} \times F_1$	$1.11 \pm 0.12 \text{ de}$	$1.20 \pm 0.29 \text{ fgh}$	14.20 ± 2.0	$10.32 \pm 2.5 \text{ a-d}$	$12.26 \pm 2.5 \text{ a-d}$	$8.44 \pm 1.3 \text{ def}$
$K_{70} \times F_2$	$1.43 \pm 0.35 \text{ a}$	$1.67 \pm 0.20 \text{ a}$	13.63 ± 3.0	$9.60 \pm 1.5 \text{ de}$	$13.46 \pm 1.4 \text{ a}$	$9.50 \pm 0.7 \text{ a}$
$K_{70} \times F_3$	$0.80 \pm 0.47 \text{ f}$	$1.03 \pm 0.24 \text{ h}$	12.63 ± 2.1	$10.16 \pm 3.1 \text{ a-e}$	$11.61 \pm 3.0 \text{ a-d}$	$8.93 \pm 1.2 \text{ a-e}$
$K_{140} \times F_0$	$1.16 \pm 0.35 \text{ cde}$	$1.47 \pm 0.15 \text{ bcd}$	13.50 ± 2.4	$9.84 \pm 1.5 \text{ a-e}$	$11.51 \pm \text{bcd}$	$8.30 \pm 2.6 \text{ ef}$
$K_{140} \times F_1$	$1.23 \pm 0.20 \text{ cd}$	$1.33 \pm 0.47 \text{ def}$	14.51 ± 2.5	$10.81 \pm 2.0 \text{ abc}$	$12.10 \pm 4.8 \text{ a-d}$	$9.26 \pm 2.1 \text{ abc}$
$K_{140} \times F_2$	$1.17 \pm 0.19 \text{ cde}$	$1.27 \pm 0.28 \text{ efg}$	15.17 ± 0.8	$11.33 \pm 2.6 \text{ a}$	$13.14 \pm 3.6 \text{ ab}$	$9.16 \pm 1.4 \text{ abc}$
$K_{140} \times F_3$	$1.40 \pm 0.17 \text{ ab}$	$1.37 \pm 0.13 \text{ c-f}$	13.27 ± 0.4	$10.50 \pm 1.2 \text{ a-d}$	$13.30 \pm 2.7 \text{ ab}$	$9.03 \pm 0.8 \text{ a-d}$
$K_{210} \times F_0$	$1.17 \pm 0.18 \text{ cde}$	$1.13 \pm 0.20 \text{ gh}$	13.13 ± 2.6	$9.90 \pm 3.3 \text{ b-e}$	$10.93 \pm 2.5 \text{ d}$	$8.96 \pm 0.4 \text{ a-e}$
$K_{210} \times F_1$	$1.07 \pm 0.22 \text{ e}$	$1.03 \pm 0.20 \text{ h}$	14.12 ± 3.5	$10.43 \pm 1.7 \text{ a-d}$	$12.93 \pm 2.1 \text{ abc}$	$9.20 \pm 1.3 \text{ abc}$
$K_{210} \times F_2$	$1.17 \pm 0.26 \text{ cde}$	$1.07 \pm 0.09 \text{ h}$	14.23 ± 1.0	$10.99 \pm 1.5 \text{ ab}$	$11.16 \pm 2.1 \text{ cd}$	$8.86 \pm 1.5 \text{ a-e}$
$K_{210} \times F_3$	$1.46 \pm 0.35 \text{ a}$	$1.60 \pm 0.46 \text{ ab}$	13.47 ± 2.4	$10.39 \pm 3.5 \text{ a-d}$	$13.07 \pm 1.8 \text{ ab}$	$9.00 \pm 0.6 \text{ a-d}$
Boll weight (g)			Seed cotton yield (kg ha^{-1})			
$K_0 \times F_0$	$5.28 \pm 1.5 \text{ de}^{\#}$	$4.55 \pm 0.4^{\text{ns}}$	$4739.6 \pm 118.6 \text{ g}^{\#}$	$4272.8 \pm 137.8 \text{ e}^{\#}$		
$K_0 \times F_1$	$5.18 \pm 2.2 \text{ de}$	4.62 ± 0.9	$5039.1 \pm 63.6 \text{ fg}$	$4056.5 \pm 97.2 \text{ e}$		
$K_0 \times F_2$	$5.14 \pm 3.0 \text{ e}$	4.60 ± 0.4	$5392.7 \pm 115.4 \text{ def}$	$4276.3 \pm 90.8 \text{ e}$		
$K_0 \times F_3$	$5.49 \pm 0.6 \text{ cde}$	4.79 ± 1.7	$4932.2 \pm 68.4 \text{ fg}$	$4547.8 \pm 104.0 \text{ de}$		
$K_{70} \times F_0$	$5.69 \pm 3.6 \text{ cde}$	4.61 ± 0.8	$5216.1 \pm 118.7 \text{ efg}$	$4540.6 \pm 113.1 \text{ de}$		
$K_{70} \times F_1$	$5.26 \pm 0.8 \text{ de}$	4.76 ± 1.7	$5423.3 \pm 116.7 \text{ def}$	$4138.9 \pm 51.4 \text{ e}$		
$K_{70} \times F_2$	$5.73 \pm 1.2 \text{ cde}$	4.71 ± 1.0	$5894.5 \pm 136.4 \text{ a-d}$	$4909.5 \pm 83.1 \text{ cd}$		
$K_{70} \times F_3$	$5.99 \pm 1.6 \text{ abc}$	4.86 ± 0.3	$5797.5 \pm 133.9 \text{ a-e}$	$4596.7 \pm 70.2 \text{ de}$		
$K_{140} \times F_0$	$5.21 \pm 0.5 \text{ de}$	4.55 ± 0.3	$5869.9 \pm 175.1 \text{ a-d}$	$4901.1 \pm 56.8 \text{ cd}$		
$K_{140} \times F_1$	$5.38 \pm 0.3 \text{ cde}$	4.80 ± 0.9	$5926.0 \pm 114.6 \text{ a-d}$	$4931.2 \pm 152.3 \text{ cd}$		
$K_{140} \times F_2$	$5.71 \pm 1.4 \text{ cde}$	4.78 ± 0.4	$6115.2 \pm 96.5 \text{ abc}$	$5602.0 \pm 136.6 \text{ b}$		
$K_{140} \times F_3$	$6.42 \pm 1.6 \text{ ab}$	5.03 ± 0.5	$5762.3 \pm 178.7 \text{ b-e}$	$5003.1 \pm 187.2 \text{ cd}$		
$K_{210} \times F_0$	$5.56 \pm 0.2 \text{ cde}$	4.91 ± 0.7	$5717.6 \pm 117.0 \text{ cde}$	$4451.0 \pm 156.1 \text{ de}$		
$K_{210} \times F_1$	$5.85 \pm 0.6 \text{ bcd}$	5.02 ± 1.2	$5835.9 \pm 170.9 \text{ a-e}$	$4485.4 \pm 103.2 \text{ de}$		
$K_{210} \times F_2$	$6.06 \pm 0.6 \text{ abc}$	5.00 ± 0.8	$6375.5 \pm 70.0 \text{ ab}$	$5390.8 \pm 73.3 \text{ bc}$		
$K_{210} \times F_3$	$6.64 \pm 1.8 \text{ a}$	5.11 ± 0.7	$6428.9 \pm 127.2 \text{ a}$	$6185.5 \pm 99.3 \text{ a}$		

[#]The means followed by different same letters within a column are statistically different from each other ($p < 0.05$), ns=non-significant. K_0 =control, $K_{70}=70 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, $K_{140}=140 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, and $K_{210}=210 \text{ kg ha}^{-1} \text{ K}_2\text{SO}_4$, F_0 =control, F_1 =humic acid (150 g in 100 L water), F_2 =micro active combination [Fe (7%), Zn (7%), B (1%), Mn (5%), Mo (0.05%), Cu (1%)] (250 g in 100 L water), and F_3 =specially designed nutrient solution (500 g urea (46% N)+500 g K_2SO_4 +100 g zinc sulfate+100 g micro active combination in 100 L water)

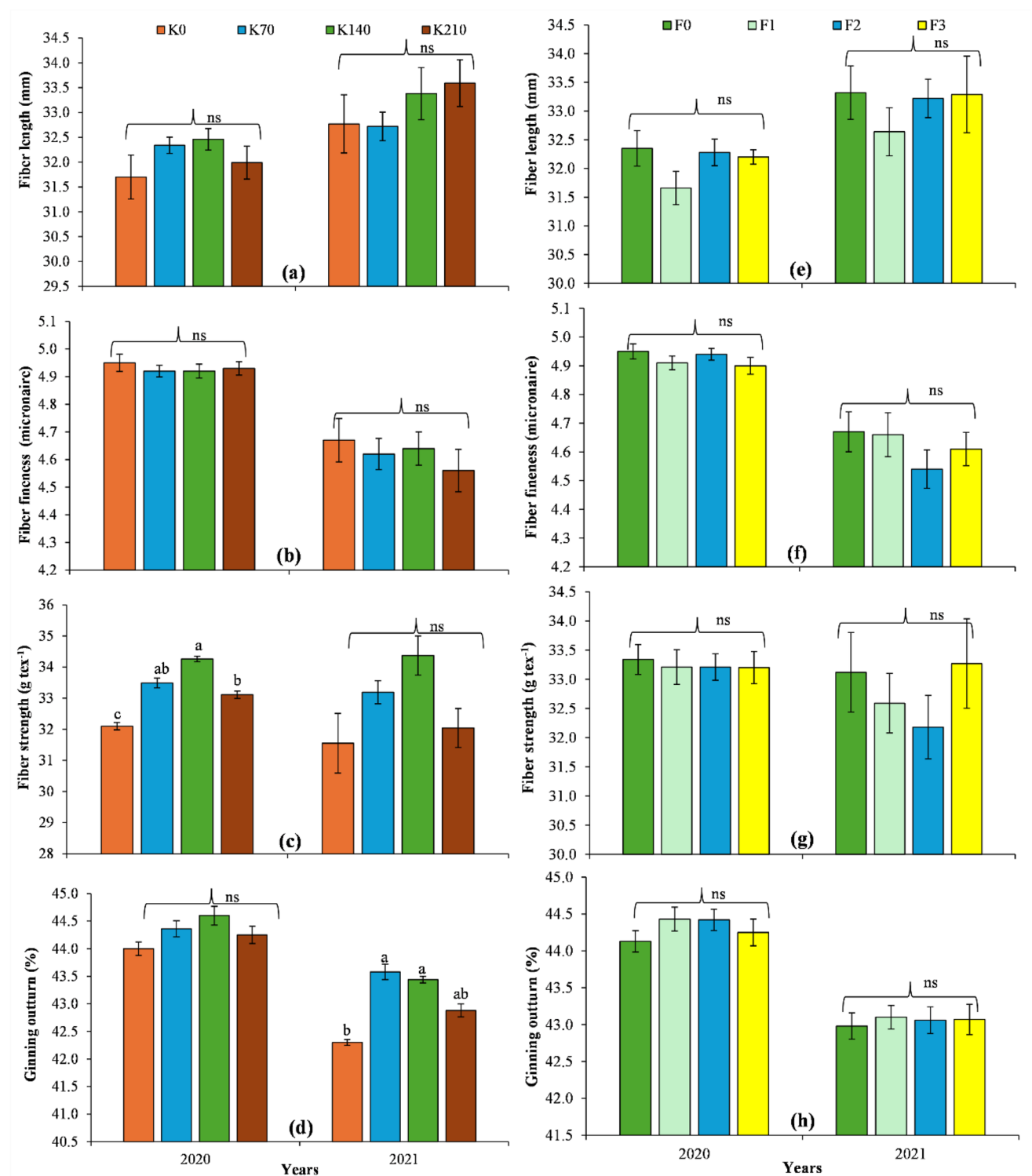


Fig. 3 The effect of different soil-applied potassium doses (a–d) and foliar fertilization treatments (e–h) on ginning outturn and fiber quality traits of cotton. The error bars are standard errors of the means ($n=3$). The means with different letters are significantly different from each other, whereas ns represents non-significant differences among the respective means. K_0 =control, K_{70} =70 kg ha^{-1} K_2SO_4 , K_{140} =140 kg

ha^{-1} K_2SO_4 , and K_{210} =210 kg ha^{-1} K_2SO_4 , F_0 =control, F_1 =humic acid (150 g in 100 L water), F_2 =micro active combination [(Fe (7%), Zn (7%), B (1%), Mn (5%), Mo (0.05%), Cu (1%)) (250 g in 100 L water), and F_3 =specially designed nutrient solution (500 g urea (46% N)+500 g K_2SO_4 +100 g zinc sulfate+100 g micro active combination in 100 L water)

Table 4 Interactive effect of different soil-applied potassium doses and foliar fertilization treatments and their interaction on ginning outturn and fiber quality traits of cotton

Interactions	Fiber length (mm)		Fiber fineness (micronaire)		Fiber strength (g tex ⁻¹)		Ginning outturn (%)	
	2020	2021	2020	2021	2020	2021	2020	2021
K ₀ ×F ₀	31.44±1.8 ^{ns}	34.39±5.8 ^{ns}	4.96±0.3 ^{ns}	4.79±0.9 ^{ns}	32.32±1.3 ^{ns}	31.98±1.2 ^{ns}	43.80±3.9 ^{ns}	42.31±1.4 ^{ns}
K ₀ ×F ₁	31.10±2.0	31.22±2.0	5.00±0.3	4.80±2.6	31.75±1.6	31.50±0.5	44.12±1.2	42.46±0.7
K ₀ ×F ₂	32.27±2.3	33.14±2.0	4.98±0.4	4.48±1.6	32.23±3.1	30.17±1.7	44.06±2.8	42.26±0.7
K ₀ ×F ₃	31.97±2.4	32.34±2.2	4.86±1.1	4.62±0.2	32.08±1.9	32.57±2.0	44.07±2.3	42.20±1.1
K ₇₀ ×F ₀	32.85±1.2	32.11±1.2	4.99±0.3	4.57±0.8	33.58±1.8	34.65±0.3	44.20±2.2	43.51±4.7
K ₇₀ ×F ₁	32.12±1.3	32.63±4.5	4.89±0.2	4.66±1.4	33.61±1.7	32.11±0.6	44.40±1.9	43.57±2.0
K ₇₀ ×F ₂	31.87±0.8	32.66±6.2	4.92±0.7	4.58±1.5	33.50±1.7	32.88±0.2	44.66±2.1	43.59±0.4
K ₇₀ ×F ₃	32.55±0.1	33.48±3.0	4.89±0.2	4.68±1.3	33.27±1.5	33.14±1.3	44.20±5.2	43.67±4.0
K ₁₄₀ ×F ₀	32.85±1.4	33.16±2.5	4.95±0.5	4.73±0.5	34.28±2.5	34.27±2.2	44.60±1.8	43.23±0.3
K ₁₄₀ ×F ₁	32.27±2.6	32.48±6.1	4.83±0.5	4.65±1.5	34.26±1.7	34.35±1.4	44.80±3.1	43.53±1.3
K ₁₄₀ ×F ₂	32.60±2.2	33.86±2.0	4.95±0.4	4.52±1.8	34.06±0.6	33.64±1.3	44.16±1.1	43.53±0.8
K ₁₄₀ ×F ₃	32.13±1.4	34.03±1.1	4.95±0.5	4.64±1.0	34.44±1.9	35.26±2.0	44.86±2.3	43.49±1.5
K ₂₁₀ ×F ₀	32.24±2.0	33.62±3.4	4.91±1.0	4.61±2.7	33.17±1.5	31.59±0.9	43.94±2.1	42.90±2.3
K ₂₁₀ ×F ₁	31.14±1.3	34.23±1.8	4.93±0.3	4.55±0.5	33.20±2.2	32.40±0.3	44.40±1.7	42.86±2.5
K ₂₁₀ ×F ₂	32.42±1.5	33.21±2.0	4.94±0.3	4.59±1.2	33.05±1.2	32.06±2.9	44.80±3.5	42.87±3.2
K ₂₁₀ ×F ₃	32.18±0.9	33.31±2.4	4.93±0.4	4.50±1.9	33.01±1.3	32.11±1.12	43.86±2.5	42.93±2.8

[#]The means followed by different same letters within a column are statistically different from each other ($p < 0.05$), ns=non-significant. K₀=control, K₇₀=70 kg ha⁻¹ K₂SO₄, K₁₄₀=140 kg ha⁻¹ K₂SO₄, and K₂₁₀=210 kg ha⁻¹ K₂SO₄, F₀=control, F₁=humic acid (150 g in 100 L water), F₂=micro active combination [(Fe (7%), Zn (7%), B (1%), Mn (5%), Mo (0.05%), Cu (1%)] (250 g in 100 L water), and F₃=specially designed nutrient solution (500 g urea (46% N)+500 g K₂SO₄+100 g zinc sulfate+100 g micro active combination in 100 L water)

Table 5 Economic analysis of cotton grown under different soil-applied potassium doses and foliar fertilization treatments

Treatments	Total Expenditure (USD ha ⁻¹)		Gross Income (USD ha ⁻¹)		Net Income (USD ha ⁻¹)		BCR	
	2020	2021	2020	2021	2020	2021	2020	2021
K ₀ ×F ₀	610	1131	976	1257	366	126	1.60	1.11
K ₀ ×F ₁	619	1140	1037	1193	418	53	1.68	1.05
K ₀ ×F ₂	625	1146	1110	1258	485	112	1.78	1.10
K ₀ ×F ₃	629	1150	1015	1338	386	188	1.61	1.16
K ₇₀ ×F ₀	632	1153	1074	1335	442	183	1.70	1.16
K ₇₀ ×F ₁	641	1162	1117	1217	476	55	1.74	1.05
K ₇₀ ×F ₂	647	1168	1214	1444	567	276	1.88	1.24
K ₇₀ ×F ₃	651	1172	1194	1352	543	180	1.83	1.15
K ₁₄₀ ×F ₀	654	1175	1209	1442	555	267	1.85	1.23
K ₁₄₀ ×F ₁	663	1184	1220	1450	557	266	1.84	1.22
K ₁₄₀ ×F ₂	669	1190	1259	1648	590	458	1.88	1.38
K ₁₄₀ ×F ₃	673	1194	1186	1472	513	278	1.76	1.23
K ₂₁₀ ×F ₀	676	1197	1177	1309	501	113	1.74	1.09
K ₂₁₀ ×F ₁	685	1206	1202	1319	517	113	1.75	1.09
K ₂₁₀ ×F ₂	691	1212	1313	1586	622	374	1.90	1.31
K ₂₁₀ ×F ₃	695	1216	1324	1819	629	603	1.90	1.50

K₀=control, K₇₀=70 kg ha⁻¹ K₂SO₄, K₁₄₀=140 kg ha⁻¹ K₂SO₄, and K₂₁₀=210 kg ha⁻¹ K₂SO₄, F₀=control, F₁=humic acid (150 g in 100 L water), F₂=micro active combination [(Fe (7%), Zn (7%), B (1%), Mn (5%), Mo (0.05%), Cu (1%)] (250 g in 100 L water), and F₃=specially designed nutrient solution (500 g urea (46% N)+500 g K₂SO₄+100 g zinc sulfate+100 g micro active combination in 100 L water). BCR=benefit cost ratio

(Pettigrew 2008). Potassium is crucial for several biochemical and physiological processes that facilitate plant growth and development (Johnson et al. 2022). It is involved in protein synthesis, glucose metabolism, and enzyme activation (Cui and Tcherkez 2021; Wang et al. 2013). Potassium

has a crucial function in enhancing leaf development, leaf area index, and CO₂ absorption; therefore, it exerts positive impact on photosynthesis, boosts dry matter production, and ultimately enhances yield (Rawat et al. 2022; Reed 2019). Slow or weak growth in the early season results in decreased

seed cotton yield and, in some instances, reduce fiber quality (Ul-Allah et al. 2021). Potassium facilitates the active production of sugars in leaves (photosynthesis) and aids in their delivery to the growing bolls (Singh et al. 2024). Foliar fertilization enhances soil K by increasing nutrient availability during critical demand periods, alleviating stress effects, and increasing metabolic activity (Oosterhuis et al. 2013). The increased boll count and boll weight under higher K doses indicate that K enhances fruit retention and fiber growth, resulting in greater productivity (Oosterhuis et al. 2013). The obtained results on seed cotton yield are owed to the optimal functions carried out by cotton plants under continuous K supply in the current study.

The non-significant effects of K and foliar fertilizer treatments on fiber length, fineness, and strength indicate that genetic variables predominantly determine fiber quality, as documented in prior research (Chandnani et al. 2017; May 2024). The growth of cotton fibers is predominantly affected by genotype and environmental factors rather than by the availability of macronutrients (Paterson et al. 2003; Zhang et al. 2009). The notable increase in ginning outturn during 2021 under high K dose indicates that K may indirectly enhance fiber processing efficiency by facilitating seed development and lint formation.

The F_3 foliar treatment (macro + micronutrients) significantly improved yield-related traits of cotton in the current study. Foliar application of F_3 provided vital nutrients, i.e., N, P, K, Zn, Fe, B, and Cu etc. directly to the leaves, facilitating quick absorption and circumventing soil limitations. Improved nutrient availability enhanced photosynthetic efficiency, promoted vegetative growth, and improved the quantity of branches and bolls, finally resulting in higher seed cotton yield. Foliar fertilization has been proven to enhance yield components by alleviating nutrient deficits throughout essential growth phases (Temiz et al. 2009; Yaseen et al. 2013). Integrated use of soil-applied K and foliar-applied macro- and micronutrients probably improved physiological and biochemical processes of cotton in the current study, which improved yield-related attributes and seed cotton production. Foliar applied macro- and micronutrients are immediately assimilated by leaves, facilitating chlorophyll production, antioxidant enzyme function, and hormonal signals that promote growth and stress tolerance (Siddiqui et al. 2022; Tripathi et al. 2015). These activities enhance cell division and expansion, leaf area development, and glucose metabolism, hence promoting vigorous boll formation and seed development. Hence, integrated use of soil-applied K and foliar-applied macro- and micronutrients enhanced physiological processes in plant development by addressing nutritional deficiencies and mitigating environmental stress.

The economic analysis indicated that $K_{210} \times F_3$ was the most beneficial treatment, producing the largest net income and benefit-cost ratio (BCR). The economic benefit of elevated K doses is associated with enhanced seed cotton yield, which compensates for the increased fertilizer expenses. Potassium application has been reported to enhance cotton profitability through increased yield and fiber quality (Adeli and Varco 2002; Liang et al. 2025; Oliver et al. 2022). The lower economic returns in 2021 are owed to temperature and rainfall fluctuations, which can influence nutrient absorption and yield potential (Akhtar et al. 2022). The lowest net revenue and BCR observed for K_0F_0 treatment highlight that insufficient K delivery constrains both productivity and profitability, underlining its critical importance in cotton nutrition.

The results of the current study indicate that appropriate soil-applied K dose combined with foliar application of macro + micronutrients improved cotton growth, yield, and economic returns. The results warrant the use $K_{210} \times F_3$ to enhance productivity and profitability of cotton. Future research should examine the prolonged impacts of K treatment on soil fertility and investigate site-specific nutrient management strategies to improve cotton resistance under diverse climatic conditions.

5 Conclusion

This study concludes that integrated use of soil applied potassium and foliar application of macro and micronutrients significantly enhanced cotton yield-related traits, seed cotton yield, and economic returns. The application of 210 kg ha^{-1} potassium combined with foliar treatment of macro and micronutrients promoted boll development, and improved seed cotton yield. Higher benefit-cost ratio and net income were noted for the same treatment. These results denote that cotton producers should apply 210 kg ha^{-1} of potassium to the soil and foliarly apply macro and micronutrients to improve production and economic returns. Future research should investigate the prolonged impacts of potassium application on soil fertility and explore the adaptation of these methods to diverse agro-ecological contexts for sustainable cotton cultivation.

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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