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RESEARCH ARTICLE

Optimizing fertigation to enhance potassium use efficiency in cotton

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Abstract

Potassium (K) plays a vital role in cotton growth by enhancing fiber quality, boll formation and the resistance to environmental stresses. Conventional fertilization methods often lead to inefficient K uptake, limiting crop productivity and contributing to nutrient loss. This study investigates the effect of optimized fertigation on improving potassium use efficiency (KUE) in cotton. A field experiment was conducted using a randomized block design (RBD) with eight different fertigation treatments with varying nitrogen (N), phosphorus (P) and K levels. The findings revealed that drip fertigation with 125 % K (T8) significantly enhanced soil K availability, plant uptake and overall yield compared to traditional fertilization K absorption peaked during boll development, highlighting the importance of applying nutrients at the right growth stages. Additionally, the highest potassium retention was observed in the topsoil (0-15 cm), reducing nutrient losses through leaching. This study underscores the benefits of precise fertigation scheduling in enhancing nutrient efficiency, improving cotton yield and maintaining soil health. By adopting targeted nutrient management practices, cotton farmers can achieve higher productivity while promoting sustainable soil fertility.

Keywords: cotton cultivation; drip irrigation; fertigation; potassium use efficiency; soil nutrient management; sustainable agriculture

Introduction

Potassium is considered as one of the most important plant nutrients, as it is required in many physiological processes, activation of enzymes, osmoregulation, photosynthesis and protein synthesis (1). It plays a vital role in cotton fruit development, fibre quality and resistance to diseases and drought. Therefore, potassium management becomes an important consideration, particularly in soils with low native K supply or high K fixation capacity. Neglecting potassium has effects on crop yield and it increases the likelihood of threatened environmental systems from nutrient leaching. Nutrient balancing for soil health as well as maximum yield is very important in cotton production. Potassium is essential for cotton as it enhances photosynthetic activity and facilitates carbohydrate translocation developing bolls. More significantly, it helps to increase the resistance of the plant to drought, salinity and pest attacks, which are the common problems in cotton-growing areas. Traditional potassium fertilization methods have relatively low efficiency resulting in suboptimal K uptake consequently leading to poor crop performance with obvious economic implications for farmers.

Fertigation refers to the application of nutrients dissolved in irrigation water, optimizing nutrient use efficiency in crops (2). Targeted application of nutrients to reach the root zone, at the right time with the right amounts, minimizes losses due to leaching and makes nutrients available at critical growth stages (3). The site-specific nutrient management of crops by the application of fertilizers to irrigated fields depends on the soil nutrients and crop nutrient demands at different space and temporal scales. Several critical factors like soil type and potassium dynamics (4), crop growth stage and nutrient demand (5), soil potassium status (6), irrigation water quality (7), type of potassium fertilizer used (8), fertigation frequency and dosage (2), environmental factors (rainfall, temperature, etc.) (9), crop-specific potassium uptake patterns (10) must be considered when determining the effectiveness and timing of potassium fertigation strategies. These factors include the interaction of potassium with other nutrient availabilities like

N and P, scheduling of irrigations concerning nutrient mobility and availability, and how potassium fertigation interacts with soil properties like soil texture, cation exchange capacity and native potassium reserves. Among other things, much seriousness has been laid on the role of soil microbial activity in making potassium soluble and, in fact, available for uptake. This could, biologically, give means for enhanced use efficiency of potassium (KUE) (11).

The environmental ramifications of potassium management in the near optimum are indeed significant. With proper potassium fertigation practices, the risk of nutrients leaching into water bodies and subsequent pollution can be minimized while promoting a sustainable path of agriculture (12). The research is in line with current global movements that advocate for resource-efficient farming which can balance yield with economic and environmental sustainability. The focus of this research is an assessment of fertigation strategies, and an evaluation of potassium use efficiency in the cotton crop. Potassium is expected to increase the yield and quality of cotton through its application correctly timed coincidence with growth stages and period nutrient demand as well the sustainable use of the nutrient concerned (13). Specific objectives include rates and timings of potassium application, interaction trials of potassium with other nutrients, and soil health and crop performance to optimize fertigation. Through this research, farmers will be equipped with useful information for the maximization of returns in fertilizer investments with reduced environmental problems. Moreover, the project contributes to the grand challenge of sustainable cotton production by advocating its precise nutrient management and its role in increasing efficiency in resource use and ensuring environmental sustainability.

Materials and Methods

No. of field trials-2

Location of the experimental site

The field investigation I was conducted in Eastern Block Farm, Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore, India. The area under study is the western agro-climatic zone of Tamil Nadu, on latitude 11°N and 77°E longitude, at an elevation of 426.7 m above mean sea level.

The field investigation II was done in Kuppepalayam, Thondamuthur. The area under study is the western agro-climatic zone of Tamil Nadu, on latitude 11°N and 77°E longitude, at an elevation of 320 m above mean sea level.

Experimental site and soil characteristics

The experimental site I features sandy clay loam soil, classified as part of the Periyanaickenpalayam series and taxonomically identified as Vertic Ustropepts according to USDA classification. The composite soil sample obtained before the conduct of the experiment was analyzed for diverse physicochemical properties. The composite soil samples collected before initiating the experiment were analyzed for physicochemical properties using standard procedures. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-water suspension using a digital pH and EC meter (14). Organic carbon was estimated by the Walkley and Black wet oxidation method (15). Available nitrogen was determined using the alkaline permanganate method (16), phosphorus by Olsen's method (17) and potassium by neutral normal ammonium acetate extraction (14). Soil texture was analyzed using the international pipette method (18) and bulk density was estimated using the core method (19). The pH was slightly alkaline (8.35), exhibiting low soluble salts (EC = 0.68), medium available phosphorus (16 kg/ha), low available nitrogen (205 kg/ha) and high accessible potassium (372 kg/ha).

The experimental site II features sandy loam soil, classified as part of the Palathurai series and taxonomically identified as Vertic Ustropepts according to USDA classification. The composite soil sample obtained before the conduct of the experiment was analyzed for diverse physicochemical properties. The pH was slightly alkaline (8.2), exhibiting low soluble salts (EC = 0.41), medium available phosphorus (27.6 kg/ha), low available nitrogen (171 kg/ha) and high accessible potassium (334.8 kg/ha).

Crop, variety and season

Cotton variety CO17 was chosen for study which is a short duration genotype which possesses zero monopodia with short sympodial length and synchronized boll maturity (20).

Experimental design

The research was structured employing RBD (randomized block design) with 3 replications. Eight treatments were evaluated, including an absolute control (no fertilization) and varying levels of potassium (K), phosphorus (P) and nitrogen (N), application through fertigation.

Treatment details

The treatment details are provided in Table 1.

Fertilizer application schedule

Based on the treatment recommendation, a fertilizer solution was formulated by dissolving an appropriate quantity of each fertilizer in water and subsequently pumped into the irrigation system via a venturi assembly for easy delivery through emitters (Table 2).

Irrigation water management

Irrigation was first applied at the time of seeding, and then on the third day after seeding establishment. Drip irrigation was applied to cotton at crucial growth phases, which include the

Table 1. Treatment details

T1	Absolute control (no NPK)
T2	Drip Fertigation with 100 % RDF (Recommended Dose of Fertilizer)
T3	Drip Fertigation with 75 % N + 100 % P and K of RDF
T4	Drip Fertigation with 125 % N + 100 % P and K of RDF
T5	Drip Fertigation with 75 % P + 100 % N and K of RDF
T6	Drip Fertigation with 125 % P + 100 % N and K of RDF
T7	Drip Fertigation with 75 % K + 100 % N and P of RDF
T8	Drip Fertigation with 125 % K + 100 % N and P of RDF

Table 2. Fertilizer application schedule

Seedling stage	10 % of the total NPK
Vegetative stage	20 % of the total NPK
Square formation	30 % of the total NPK
50 % flowering stage	20 % of the total NPK
Boll formation and development Stage	10 % of the total NPK

seedling, vegetative, square formation, 50 % blooming, boll formation and boll development stages, as per the treatment schedule. The experimental plots received successive irrigations at 7-day interval schedule, depending on the soil and weather conditions.

Potassium uptake

Cotton plant potassium uptake was assessed periodically by taking organ samples (root, stem and leaves) from cotton plants at various growth stages. The potassium concentration in these samples was analyzed by atomic absorption spectroscopy. The uptake patterns were then judged against the role of potassium incorporation in plant growth and productivity.

Soil available potassium

Potassium content in soil was evaluated at the beginning and end stages of the experiment using the ammonium-acetate method (14). This helps determine the contribution of available soil potassium to plant uptake under different fertigation treatments. Samples were taken from different depths (0-30 cm and 30-60 cm) to monitor vertical movement in potassium.

Potassium dynamics

The periodic soil test during the growing season was based on the dynamics of potassium within the soil. Potassium leaching, volatilization and fixation were determined in the soils to know how fertigation has affected the changes in the soil potassium availability. The irrigation management practices will help optimize the potassium consumption of the cotton plants as well.

Potassium use efficiency

Potassium use efficiency was estimated by evaluating the potassium absorbed by the plant relative to its total application through fertigation with potassium. The trials were conducted under several fertigation strategies involving various application rates and frequencies. KUE was estimated based on yield and potassium uptake efficiency. Potassium use efficiency was calculated using the following efficiency indices.

Agronomic efficiency (AE)

$$AE = \frac{\text{Yield in fertilized plot - Yield in control plot}}{\text{Potassium applied } \left(\frac{kg}{ha}\right)} \qquad \text{Eq. 1}$$

Recovery efficiency (RE)

$$RE = \frac{\text{Potassium uptake in fertilized plot - Potassium uptake in control plot}}{\text{Potassium applied } \left(\frac{kg}{ha}\right)} \qquad \text{Eq. 2}$$

Partial factor productivity (PFP)

$$PFP = \frac{\text{Yield in fertilized plot}}{\text{Potassium applied } \left(\frac{kg}{ha}\right)} \qquad \text{Eq. 3}$$

Methodology for graph generation

Several graphical methods were employed to effectively visualize the influence of fertigation on soil-available potassium, potassium uptake and potassium distribution. The information sourced from various treatments and different growth stages was analyzed and illustrated using Python-based visualization tools (Matplotlib, Seaborn and NumPy) for clarity, correctness and professional presentation.

Heatmap for potassium uptake at different soil depths and fertilizer levels

A heatmap was generated to illustrate the variation in potassium uptake at different soil depths and fertilizer levels. Uptake values at different depth-fertilizer combinations were represented using bars The dataset with soil potassium values for each treatment across six growth stages was structured in a matrix format. A heatmap was created using Seaborn's heatmap function, with potassium levels represented through a gradient color scale (YlGnBu colormap). The x-axis and y-axis were labelled with growth stages and treatments, respectively. The final heatmap was exported as a high-resolution image (300 dpi) for publication purposes.

Line graph for potassium uptake and soil available potassium and potassium use efficiency

A line graph was used to track potassium uptake and soil available potassium patterns across different growth stages for multiple fertigation treatments. The uptake trend over time was analyzed to identify the efficiency. The dataset containing potassium uptake values for each treatment across growth stages was structured. A line plot was generated using Matplotlib, with growth stages on the x-axis and potassium uptake on the y-axis. Different line styles were used to differentiate treatments, with T8 highlighted in red as the best-performing treatment T8 performed best due to 125 % potassium with balanced nitrogen and phosphorus, enhancing boll formation, fiber quality and nutrient uptake. The fertigation matched crop demand using growth curves and tensiometer-based scheduling, improving nutrient efficiency. Potassium-rich treatment also improved photosynthesis, enzyme activity and water-use efficiency, leading to higher yield and quality. The final graph was saved as a high-resolution image (300 dpi).

Software and tools used

- Python 3.11.
- Libraries: Matplotlib, Seaborn, NumPy.
- Graph Export Format: PNG (300 dpi, high resolution for publication).

Each of these visualizations provides insights into the effectiveness of fertigation in potassium management for cotton cultivation.

Results and Discussion

Potassium uptake patterns

Potassium uptake was higher in black soil compared to red soil across all the growth stages (Fig. 1). The highest uptake was recorded in T8 (125 % K + 100 % N&P), with black soil showing 188.3 mg/kg at boll development, whereas red soil recorded 184.8 mg/kg (Table 3). This difference is due to black soil's higher clay content and cation exchange capacity which improves potassium retention and uptake (21). The lowest uptake was observed in T1 (absolute control), highlighting the necessity of fertigation for optimal potassium absorption. The different RDF levels (75 %, 100 %, 125 %) supplied through fertigation in split ratios at the peak growth stages exerted a significant influence on potassium uptake. The highest K uptake was recorded with a 125 % dose of K along with 100 % N and P applied through fertigation, registering values of 6.3, 67.3, 97.9, 136, 165 and 188.3 kg ha^{-1} in black soil and 6.0, 64.1, 96.1, 133.6, 162.8 and 184.8 kg ha^{-1} in red soil, at seedling, vegetative, squaring, 50 % flowering, boll formation and boll development stages respectively. Among the treatments, T1 (absolute control with no NPK) recorded the lowest nutrient uptake across all growth stages in both soils. Uptake values progressively increased from seedling to boll development, with slightly higher values in black soil than red soil at each stage (Fig. 1). The absolute control treatment recorded the lowest potassium uptake, emphasizing the importance of fertigation in enhancing nutrient availability and uptake efficiency in cotton. This highlights that fertigation with an enhanced dose of potassium significantly improves nutrient absorption at critical growth stages and absolute control. This is because potassium plays a major role in better root vigor development. Potassium deficiency may lead to root elongation along with lateral root formation of plants thus adversely affecting the nutrient uptake capacity of soil (22). Cotton crops are found to be more sensitive to potassium when compared to major field crops and often show symptoms of K deficiency (23). Therefore, a need for potassium increases dramatically at successive growth stages, especially at the reproductive development stages. Concerning water relations, K is the most critical macronutrient for plants, as it directly affects physiological processes as well as regulates cotton's plant developmental attributes (24). K's involvement in stomatal regulation and cell water relations is crucial in the provision of drought resistance to plants in field conditions. Consequently, potassium fertilizers are implemented to mitigate the consequences of drought stress (DS) and drought sensitivity.

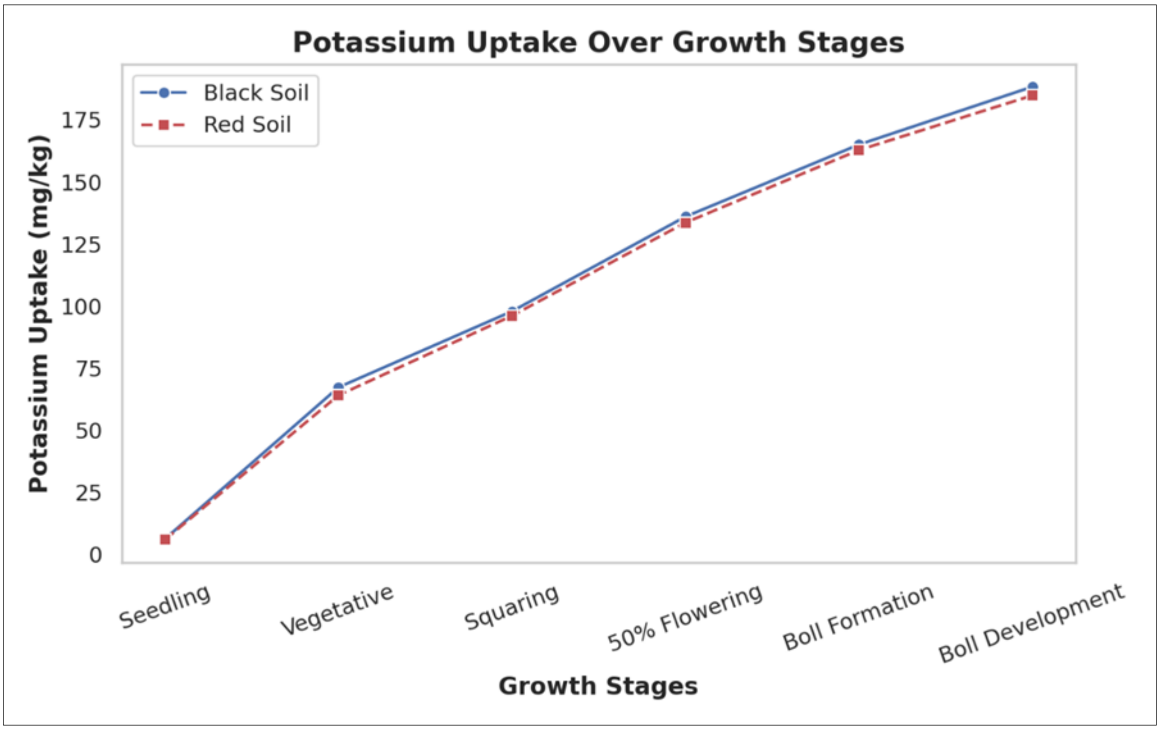

Fig. 1. Potassium uptake over growth stages.

Table 3. Impact of fertigation on potassium uptake

	I crop (black soil)							II crop (red Soil)					
Tr	**Seedling**	**Vegetative**	**Squaring**	**50 % flowering**	**Boll formation**	**Boll development**	**Tr**	**Seedling**	**Vegetative**	**Squaring**	**50 % flowering**	**Boll formation**	**Boll develop ment**
T1	3.7	45.7	78.1	114.6	144.2	169.2	T1	3.5	44.6	75.9	113.3	142.8	162.2
T2	4.9	58.1	89.4	124.3	155	173.3	T2	5	54.3	86.8	124.8	151.7	171.3
T3	4.3	50.8	83	119	150.2	169.4	T3	4	49.1	80.1	117.9	146.6	168
T4	5.3	59	90.8	130.2	158.3	176	T4	5.1	57.2	89	126.8	154.9	173.9
T5	4.8	55	85.2	122.9	153.7	171.7	T5	4.7	50.1	81.8	122	151.4	169.6
T6	5.7	62.2	93	131.6	159	181.1	T6	5.5	59.6	91.9	129	159	179
T7	4.6	52.8	87	120.8	151.6	170	T7	4.5	51.7	84.1	120.2	149.3	169.3
T8	6.3	67.3	97.9	136	165	188.3	T8	6	64.1	96.1	133.6	162.8	184.8
SEd	0.29	3.2	5.0	7.1	8.7	9.9	**SEd**	0.27	3.1	4.9	7.0	8.6	9.7
CD (p = 0.05)	0.62	6.9	10.7	14.2	18.2	21.3	**CD (p = 0.05)**	0.60	6.6	10.5	14.2	18.2	21.2

Stomatal closure due to DS can result in a reduction in net photosynthesis and the transport of photosynthates to reproductive parts, as well as a poor intercellular CO_2 concentration (4). Fertigation with water-soluble fertilizers enables the direct application of nutrients to the rhizosphere, thereby meeting the physiological requirements of the crops for improved vegetative and reproductive development (25) (5). The application of a higher and optimal dose (125 % and 100 %) of fertilizers through fertigation resulted in the maximum uptake of nutrients at all crop growth-sensitive stages. This suggests that the availability of nutrients was increased by increasing the dose of fertilizers, which in turn led to a higher uptake by plants (26). Comparable results were compared regarding increased nutrient uptake in conjunction with increased fertilizer levels under drip fertigation (27). In addition, the application of nutrients in a greater number of splits in drip fertigation resulted in minimal or no wastage of nutrients, either through deep percolation or volatilization, which ultimately led to increased nutrient uptake. This facilitated the crop's production of a bountiful yield, improved growth and yield attributes (28, 29). A line graph (Fig. 2) was generated to illustrate the potassium uptake pattern over different growth stages for various fertigation treatments. The uptake of potassium steadily increased from the seedling stage to boll development, with T8 showing the highest values at each stage.

Potassium uptake in T8 increased from seedling stage to boll development, emphasizing the importance of higher potassium application for efficient nutrient absorption. The consistent uptake trend across all treatments suggests that fertigation ensures a continuous and steady supply of potassium, which is essential for optimal plant metabolism, cell expansion and boll formation.

Soil available potassium

The available potassium content increased as the crop progressed with black soil showing consistently higher values than red soil. The available potassium content increased as the crop progressed, with black soil consistently showing higher values than red soil. This increase can be attributed to regular fertigation, which supplied K in sync with crop demand, and the mineralization of soil reserves. Higher retention capacity in black soil further contributed to sustained availability (Table 4). The highest soil available potassium was recorded with a 125 % dose of K along with 100 % N and P applied through fertigation, registering values of 365.2, 467.1, 543.8, 567.8, 647.9, 667 kg ha^{-1} in black soil and 345.7, 445.3, 536.3, 557.3, 621.3, 647.4 kg^{-1}ha in red soil at seedling, vegetative, squaring, 50 % flowering, boll formation and boll development stages respectively. Among the treatments, T1 *i.e.* the absolute control (no NPK) recorded comparatively lower uptake values of 284.4, 319.8, 382.4, 474.4, 526.1, 541.2 kg ha^{-1} in black soil and 269.3, 310.6, 368.2, 421.2, 502.8, 510.3 kg/ha in red soil at seedling, vegetative, squaring, 50 % flowering, boll formation and boll development stages. In T8, black soil recorded 667 mg/kg, whereas red soil recorded 647.4 mg/kg at the boll development stage. The lowest potassium levels were observed in T1 (control) recording 541.2 mg/kg in black soil and 510.3 mg/kg in red soil (Fig. 2). The results indicate that the black soil retains potassium better due to its higher organic matter and clay content, whereas red soil exhibits more leaching losses. The fertigation scheduling with different RDF levels in split ratios significantly influenced the soil available potassium status. The absolute control treatment registered the lowest soil available potassium, indicating the importance of fertigation in maintaining higher soil potassium reserves throughout the crop growth cycle. The yield of cotton can be limited by the quantity of available nutrients in the soil, particularly if the supply does not meet the plant's needs. The yield was enhanced by increasing the fertilization level from 100 % to 125 %. Increased levels of fertilizer application increased the concentration of available nutrients in soil. There was an elevation in the availability of N, P and K in the soil during successive crop growth stages, *viz.*, seedling, vegetative, squaring, 50 % flowering, boll formation and boll development. However, a decrease in nutrient concentration was observed during the post-harvest

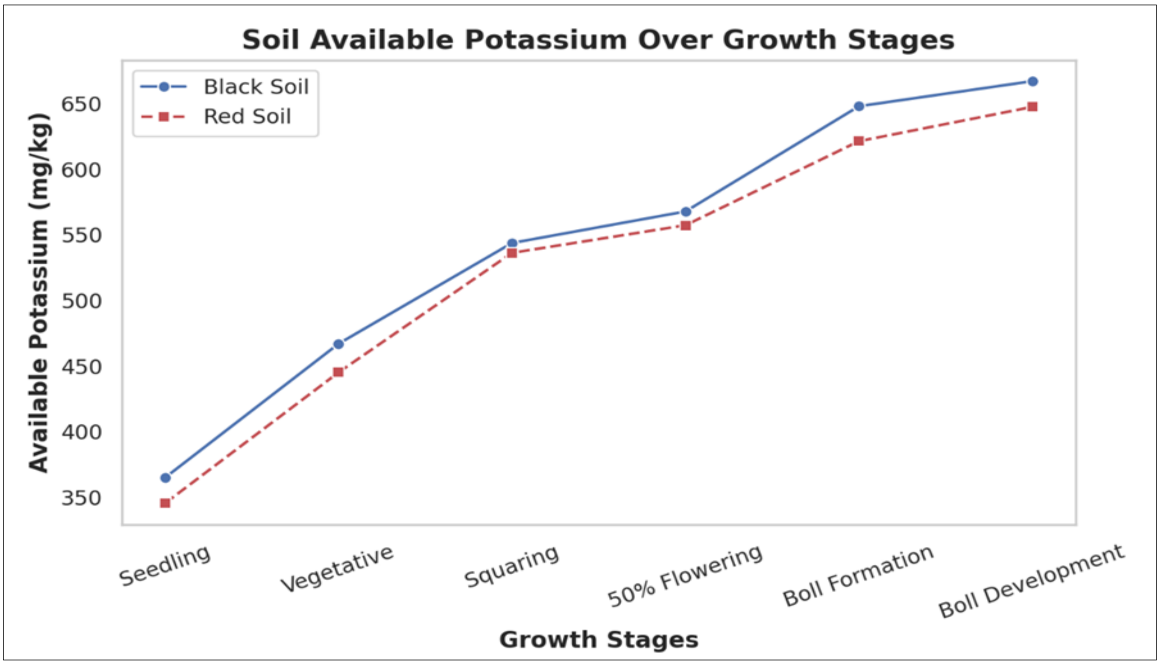

Fig. 2. Soil available potassium over growth stages.

Table 4. Impact of fertigation on soil available potassium

Tr	Seedling	Vegetative	Squaring	50 % flowering	Boll formation	Boll development	Tr	Seedling	Vegetative	Squaring	50 % flowering	Boll formation	Boll development
I crop (black soil)							II crop (red Soil)						
T1	284.4	319.8	382.4	474.4	526.1	541.2	T1	269.3	310.6	368.2	421.2	502.8	510.3
T2	331.9	403.3	493.3	514.2	596.4	614	T2	324.9	401.5	474.4	508	587.5	603.6
T3	312.4	375.1	411.6	508.4	567	586.2	T3	295.9	350.8	407	469.4	525.1	540.3
T4	337.9	407.9	505.3	522.3	602.6	621.7	T4	328.6	401	486.4	510.4	595.8	614.7
T5	328.4	397.8	476.2	510.1	591.1	609.7	T5	316.2	383.2	441.2	498.4	585.3	586.7
T6	340.7	412.4	514.9	533.8	607	624.8	T6	335.1	407.1	500.6	512.2	601.2	619.8
T7	323.6	386.3	433	504.7	588.4	606.4	T7	305.2	366.4	420.9	485.1	569.1	548.8
T8	365.2	467.1	543.8	567.8	647.9	667	T8	345.7	445.3	536.3	557.3	621.3	647.4
SEd	18.6	22.6	27.1	29.3	33.4	34.4	**SEd**	17.9	21.9	26.3	28.1	32.5	33.4
CD (p = 0.05)	**39.9**	**46.5**	**58.3**	**60.2**	**64.2**	**65.1**	**CD (p = 0.05)**	**38.5**	**47.1**	**56.5**	**60.4**	**69.8**	**71.7**

soil. This is because of greater nutrient uptake usually occurs at the active growth stages, especially during reproductive development stages (squaring, 50 % flowering, boll formation, boll development stages) and thereafter a gradual decline in soil available N, P and K is noticed as the crop approaches harvest. Similar findings were reported previously (30).

The fertigation scheduling of water soluble fertilizers at different levels (75 %, 100 % and 125 %) in split ratios helps in maintaining an optimum moisture regime and higher nutrient concentration over the root zone region thus resulted in faster assimilation of nutrients at the peak growth stages. This might be because the application of fertilizers through drip fertigation resulted in a reduced rate of leaching and volatilization loss when compared to conventional irrigation practice, where direct soil application of fertilizers was practiced. Hence under drip fertigation, higher N, P and K dynamics were noticed in the top layers *viz*., rhizospheric region where the N, P and K nutrients are in the most available form to plants thereby resulting in higher nutrient uptake. This is concomitant with the outcomes of previous studies (31-33).

Among all treatments, T8 exhibited the highest soil available potassium, showing a significant increase from the seedling stage to boll development. This indicates that higher fertigation doses contribute to improved soil potassium retention throughout the crop cycle. The trends observed suggest that adequate potassium supply during critical growth phases, such as 50 % flowering and boll development, is essential for maximizing crop productivity.

Soil potassium dynamics

The depth wise movement of potassium varied significantly between the two soil types (Table 5). At 0-15 cm depth, potassium concentration was highest, particularly near the emitter, confirming better nutrition in black soil. Potassium concentration was highest near the emitter at 0-15 cm depth due to localized application through fertigation. In black soils with high cation exchange capacity, potassium is less mobile and gets retained near the application point. This enhances nutrient availability and root uptake efficiency in the wetted zone around the emitter. As depth increased (15-30 cm and 30-45 cm), potassium levels declined in both the soils. However, red soil exhibited a steeper decline due to its lower water holding capacity and potassium retention capacity. At 30 cm depth and 30 cm horizontal distance, potassium concentration was 167.6 mg/kg in black soil and 154.2 mg/kg in red soil, indicating greater nutrient loss in red soil. These findings suggest that fertigation is most effective in the upper root zone (0-15 cm), with potassium leaching being more prominent in red soil. The distribution of potassium below the emitter exhibited a pattern similar to that of nitrogen, specifically a progressive increase with the incremental application of RDF. Additionally, the availability of potassium was reduced at the far end of the dripper point. The maximum K distribution was observed at 125 % RDF near the dripper point (Fig. 3). The distribution progressively decreased horizontally and vertically at a distance of 30 cm from the dripper. The concentrations of soil solution K will be determined by the equilibrium and kinetic reactions that occur within various forms of soil potassium, the soil moisture content and the concentration of bivalent cations in the solution and exchange phase (34). Potassium is less mobile than nitrate; however, a uniform distribution in the wetted volume may be achieved through interactions with binding sites (35).

All high K accumulation results have been recorded in the soil depth at 0-15 cm following fertigation as contrasted to the low layer, which was at a depth of 15-30 cm. The largest quantity of K was impinged at the depth of 0-15 cm beneath the emitter. This is in accordance with previous study (17). Potassium in the surface soil may fluctuate dramatically due to varied wetting and drying and hence have a rapid fixation

Table 5. Impact of fertigation on potassium dynamics

Depth	Horizontal distance	I crop (Black soil)			II crop (Red Soil)		
		75 % RDF	100 %RDF	125 %RDF	75 % RDF	100 %RDF	125 %RDF
0-15	**0**	218.7	234.5	319.8	216.8	232.5	309.4
	15	215.7	231.8	343.6	211.6	230.3	255.6
	30	210.3	227.6	246.9	208.3	225.4	235.2
15-30	**0**	209.5	221.7	234.5	206.4	223.5	228.7
	15	202.3	218.6	220.3	200.6	204.8	219.5
	30	198.7	215.3	219.6	195.4	198.6	217.6
30-45	**0**	185.6	216.5	214.3	182.8	185.3	200.6
	15	177.3	210.7	208.5	175.3	171.5	198.3
	30	167.6	200.6	202.6	154.2	157.6	189.4

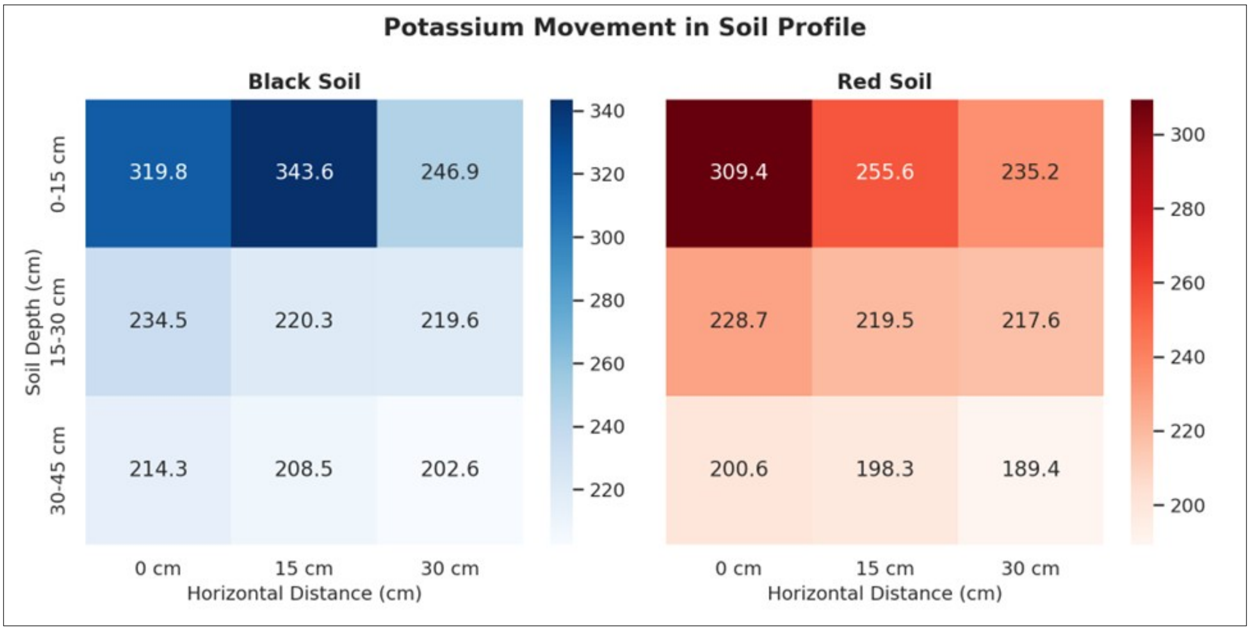

Fig. 3. Potassium uptake at different soil depths and fertilizer levels

by soil, mostly in summer. However, in this particular experiment, surface soils had notably higher soil K content than subsoils. This is because during that time, most of the applied K is withheld within the surface soil and only a little movement is taking place downwards. Net upward movement of soil water in the soil profile due to high evapotranspiration could offer a partial explanation of the slow downward movement of applied K (Fig. 4). This is supported by the outcomes of the previous study (36). One author has also described that the distribution of potassium (K) in the soil profile is characterized by a decrease in soil K content as depth increases (37). Despite the slow movement of potassium in the soil profile, its concentration at 0-15 cm increased significantly. The amount of K available is higher in the surface layer due to the K ions entering the soil exchange complex, with a very small amount moving to the deeper layer, as inferred in the previous study (38).

The distribution of K uptake varied significantly with depth and fertilizer application rates. The highest potassium uptake was observed at 0-15 cm soil depth, indicating that most of the applied potassium remains in the upper soil layers. A gradual decline in uptake was noted with increasing depth, highlighting the limited vertical movement of potassium and the necessity for proper fertigation scheduling to optimize nutrient absorption. These findings emphasize that higher fertigation doses significantly enhance potassium uptake, particularly in the topsoil layer, where active root absorption occurs.

Potassium use efficiency (KUE)

Fertigation significantly influences soil potassium availability, uptake and distribution across different soil depths. Agronomic efficiency (AE) differed between treatments; T8 (125 % K + 100 % N and P) had the highest AE, followed by T6 (125 % P + 100 % N and K). Due to improved potassium

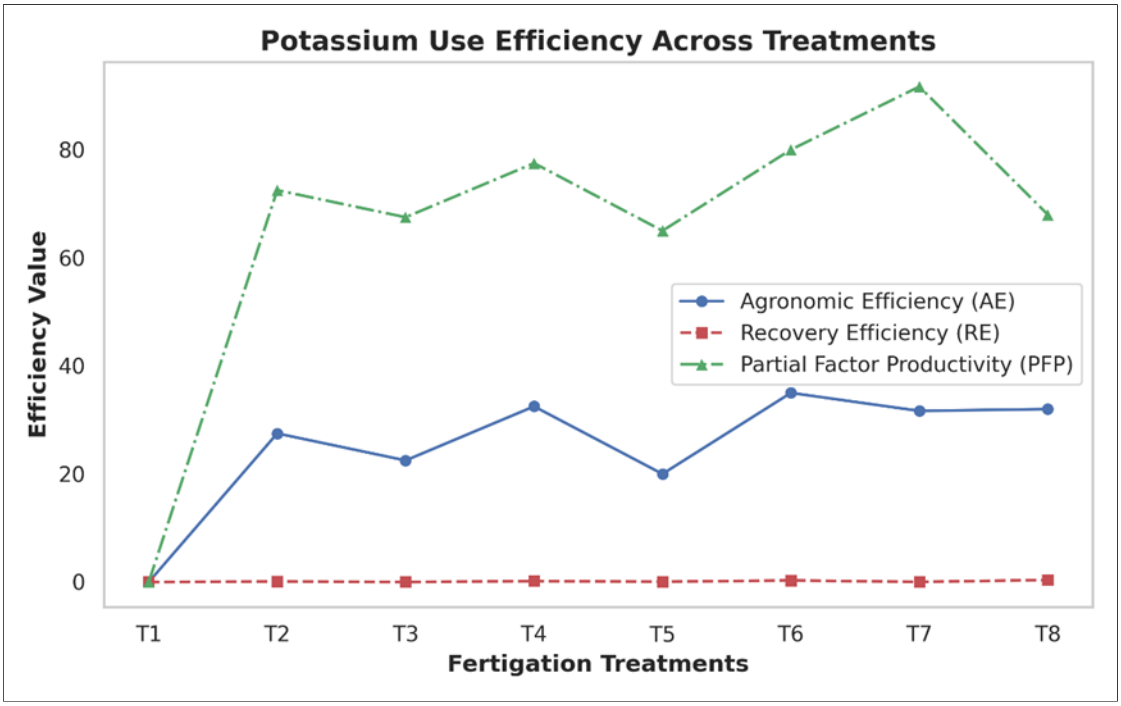

Fig. 4. Potassium use efficiency across different treatments.

availability and retention in black soil, AE was greater, increasing yield response per unit of administered potassium. In contrast, AE was significantly lower in red soil, most likely as a result of increased potassium leaching and decreased root zone nutrient availability. Recovery Efficiency (RE), which quantifies the percentage of applied potassium absorbed by the plant, was highest in T8, followed by T6 and T4. Black soil had higher RE values because of its superior cation exchange capacity (CEC) and moisture-holding qualities, which increased potassium retention and uptake efficiency. Conversely, red soil had lower RE values, reflecting higher potassium losses through leaching. This shows that red soil requires more frequent fertigation to maintain optimal potassium availability.

Partial Factor Productivity (PFP), which assesses yield per unit potassium applied, followed a similar pattern to AE and RE. T8 had the highest PFP, indicating that increased potassium treatment with balanced fertigation greatly increased yield. PFP in black soil was consistently higher across all treatments than in red soil, indicating that potassium usage was more efficient due to improved nutrient retention. Red soil had a reduced PFP, highlighting the necessity of site-specific nutrient management to reduce potassium losses. Black soil outperformed red soil in all three KUE parameters (AE, RE, PFP) due to its higher nutrient retention capacity and better soil structure. Red soil showed greater variability in KUE, suggesting that potassium fertigation scheduling should be adjusted to compensate for higher nutrient losses. The results highlight the importance of tailored potassium fertigation strategies to maximize yield and nutrient use efficiency based on soil type. Fig. 4 illustrates the potassium use efficiency across different treatments. The best management of potassium during the production of cotton for efficiency in nutrient use and increased productivity lies in the stages of boll formation and development. T8 exhibited the highest soil potassium retention. This indicates that it is the highest initial amount of potassium applied in fertigation that can hold the entire retention of potassium during the crop cycle.

From the graphical representations, it was found that T8 (the higher fertigation dose) showed the best retention of soil potassium to plant uptake at all stages of growth. Potassium uptake showed a gradual increase throughout its crop growth, peaking at the time of boll development. A 125 % RDF application significantly enhanced potassium uptake, particularly in the topsoil layer. Further, these results substantiate the need to schedule fertigation optimally to manage the potassium in a better way for cotton crops, taking care of the soil nutrient sustainability as well as crop productivity increases.

Conclusion

Black soil exhibited higher potassium uptake. Retention and availability compared to red soil due to its better CEC and organic matter content. In contrast, red soil experienced greater leaching, emphasizing the need for frequent irrigation to maintain optimal potassium levels. Fertigation results in a marked difference in the availability of soil potassium and its uptake and distribution in different soil depths. This can best be shown trough complicated or sophisticated images. The best way of managing potassium during its production in cotton for efficient utilization of nutrients and increased productivity is in the boll formation and development stages. T8 demonstrated the highest soil potassium retention. This infers that the entire retention of potassium during the crop cycle is achieved by the higher amounts of fertigation. There was a gradual increase in the uptake of potassium across different growth stages, with the package exhibiting great uptake during the period of boll development. T8, with all perspectives confirming the role of adequate potassium supply in plant growth and productivity, always outperformed others. Across all depth ranges, potassium uptake was highest from the 0-15 cm soil depth, with maximum uptake arising following 125 % RDF application. This signifies that fertilizer application at a higher rate improves absorption of nutrients, especially in the upper level of soils, where root activity is predominant.

In general, the results of the study establish that larger doses of fertigation enhance potassium retention in the soil, increase potassium uptake efficiency by plants and optimize the distribution of potassium throughout the soil profile. These findings point to the importance of careful fertigation scheduling for good potassium management which results in improving cotton yield and ensuring soil sustainability. This study emphasizes the necessity of soil-specific fertigation strategies to improve nutrient use efficiency and maintain soil fertility in crop production.

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Authors' contributions

DR carried out the experiment, analyzed the data and wrote the draft manuscript. MB, ME, BS, VR and SM conceived, designed and coordinated the experiments and corrected the manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

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

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