IMPROVING COTTON PRODUCTIVITY AND FIBER QUALITY THROUGH IMPLEMENTATION OF REDUCED TILLAGE AND BALANCED NUTRITION UNDER ARID CLIMATE

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) is a cash crop that plays a crucial role in the textile industry at global scale and Pakistan. However, its sustainable production is restricted by challenges like conventional tillage, imbalanced fertilization, water shortage and soil health degradation. Therefore, a two-year field study was conducted in Agricultural Research Institute, Ratta Kulachi, Dera Ismail Khan to compare the tillage operations coupled with nutritional regimes of balanced nitrogen (N), phosphorus (P), and potassium (K) to maintain the growth, yield and fiber quality traits of the cotton. The research treatments involved the tillage system (TS) reduced vs. conventional as main plots and NPK levels (NPK_1 = 0:0:0, NPK_2 = 200:0:0, NPK_3 = 0:120:0, NPK_4 = 0:0:150, NPK_5 = 200:120:0, NPK_6 = 200:0:150, NPK_7 = 0:120:150, NPK_8 = 200:120:150, and NPK_9 = 250:170:200 kg ha^{-1}) as subplots. The fiber quality and yield attributes of cotton were assessed after the harvest of cotton. The results of interactive effect of TS, NPK and Years were significant which influenced sympodial branches ($plant^{-1}$), ginning outturn (%) and fiber strength (g tex^{-1}) during both the years 2023 and 2024. However, balance NPK (200:120:150 kg ha^{-1}) in combination with reduced tillage consistently outperformed and yielded maximum sympodial branches (59.2 in 2024 and 57.7 in 2023), plant height (151.5 cm in 2024), bolls $plant^{-1}$ (60.7 in 2024 and 59.7 in 2023), seed cotton (2696 kg ha^{-1} in 2024 and 2646 kg ha^{-1} in 2023) and ginning outturn (71.9% in 2024 and 70.7% in 2023). This optimal fertilizer dose also improved fiber strength (30.0-31.0 g tex^{-1}) which gave the highest net returns (1003.18 US \$ ha^{-1}) with benefit cost ratio (BCR) of 2.3. This study concluded that combination of reduced tillage and NPK (200:120:150 kg ha^{-1}) adequately for sustainable cotton production under arid environment.

Keywords: Arid climate; Cotton productivity; Fiber quality; Nitrogen fertilization; Reduced tillage; Balanced NPK

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is a significant commercial crop as it holds substantial economic value for the global textile industry (Khan *et al*., 2020). The highest production of cotton is attained in subtropical and seasonally dry areas in both the northern and southern hemisphere, however most of the production takes place towards north of equator (Khan *et al*., 2025). In recent decades the of cotton is also expanded to the arid or semi warm agro-ecological regions of several countries including Pakistan, India, China, the United States, and Brazil (Bange *et al*., 2016). Cotton is very important for economy while its production is compromised every year due to poor soil fertility, deficiency in organic matter content (OMC), insect pest infestation and drought conditions due to climate change effect (Fareed *et al*., 2025; Hussain *et al*., 2025). The disturbance in soil and water dominate the production losses while the other factors involve mono cropping, conventional tillage practices, loss of macronutrient and over use of agrochemicals. The average cotton yield in Pakistan is approximately 700 kg ha^{-1} which is at least 15-20% less as compared to the top producing countries (Farooq *et al*., 2018).

The aforementioned productivity losses are also contributed by tillage practices which disturb soil structure, and contribute to the loss of nutrients and soil organic carbon. The extended use of traditional tillage methods can further degrade soil quality and increase the need for synthetic fertilizers (Boincean and Dent, 2019). Apart from the above challenge nutrients also serve as limiting factor in cotton production (Ghaffar *et al*., 2020; Ahmad *et al*., 2021). The nutritional requirements of cotton are specific as a balanced and adequate supply of nutrients across the entire growth phase serve a vital role for optimal vegetative growth, fiber quality improvement, and stress tolerance under adverse environmental conditions (Ahmad *et al*., 2022; Ahmed *et al*., 2023). The role of macronutrients in cotton is very specific as the supply of nitrogen (N) in cotton significantly influences cotton growth by improving the chlorophyll content and vegetative growth of crop (Manzoor *et al*., 2022; Usman *et al*., 2025). In addition phosphorus (P) deficiency reduce the dry matter and total biomass of cotton followed by lower regulation of carotenoids and total soluble proteins (TSP) (Venkatachalam *et al*., 2017). The lower availability of P reduces the seed development and cotton seed yield. The other limiting nutrient for cotton is potassium (P) whose deficiency decrease the process of photosynthesis, protein synthesis and enhanced carbohydrates metabolism by activating the enzymes (Kapoor *et al*., 2020; Akhtar *et al*., 2023).

The problem of water scarcity and excessive tillage can be addressed by incorporating crop residues (Ahmad *et al*., 2024) and promotion of conservation tillage systems, especially reduced tillage which enhance the retention of more than 30% moisture (Li *et al*., 2024). Additionally, the issue of nutrient losses and nutrient deficiency can be decreased by the application of synthetic fertilizers. Although tillage and nutrient application have been widely studied as a separate factor while a limited information is available on the combined effect of conservation tillage with balanced NPK fertilizer.

The available data document that the combined influence of tillage systems and nutrient application on cotton have been evaluated in prior studies, for instance the combined effect of reduced tillage with N application (Usman *et al*., 2014), similarly the influence of tillage with K application and conservation tillage with organic amendments (Ahmad *et al*., 2022). The previous studies have evaluated the influence of tillage coupled with individual nutrient management, however, the available information still remains limited regarding the response of cotton yield and fiber quality to a combination of reduced versus conventional tillage across a balanced range of NPK under the arid conditions of Dera Ismail Khan. Therefore, the present study was conducted to assess the efficiency of reduced tillage in comparison with conventional tillage and to evaluate balanced NPK combination under different tillage system for improving cotton yield and fiber quality under arid climate.

MATERIALS AND METHODS

Experimental site, soil and weather conditions: The current research was conducted on Agricultural Research Institute, Ratta Kulachi, Dera Ismail Khan (31.52884° N, 70.54715° E). The sample of soil was collected from 0-30 cm layer to characterize the key physicochemical parameters including SOM (Walkley & Black, 1934), pH and EC (soil: water), total soil N (Bremner & Mulvaney, 1982), P and K (Soltanpour, 1985), cation exchange capacity (ICARDA) and soil texture (Bouyoucos, 1951) (Table 1).

Table 1. Soil physicochemical and biological characteristics of the experimental site

Properties	Units	Values
Silt	%	51
Sand	%	6
Clay	%	43
Soil Texture	-	Silty clay
pH	-	7.8
OMC	%	0.9
Total N	mg kg^{-1}	300
Available P	mg kg^{-1}	5.6
Available K	mg kg^{-1}	191
CEC	meq c kg^{-1}	0.193
EC	dS m^{-1}	0.19

OMC= organic matter content, N=nitrogen, P=phosphorus, K=potassium, CEC=cation exchange capacity, EC= electrical conductivity, %= percentage, mg kg^{-1}= milligram per kilogram, meq c kg^{-1}= milliequivalent charge per kilogram

This trial was conducted in arid region where annual rainfall ranged from 179 mm to 350 mm and faces extended hot summer periods. The climatic conditions in second year of experiment were favorable for the production of cotton which improved the production in second year (Fig 1)

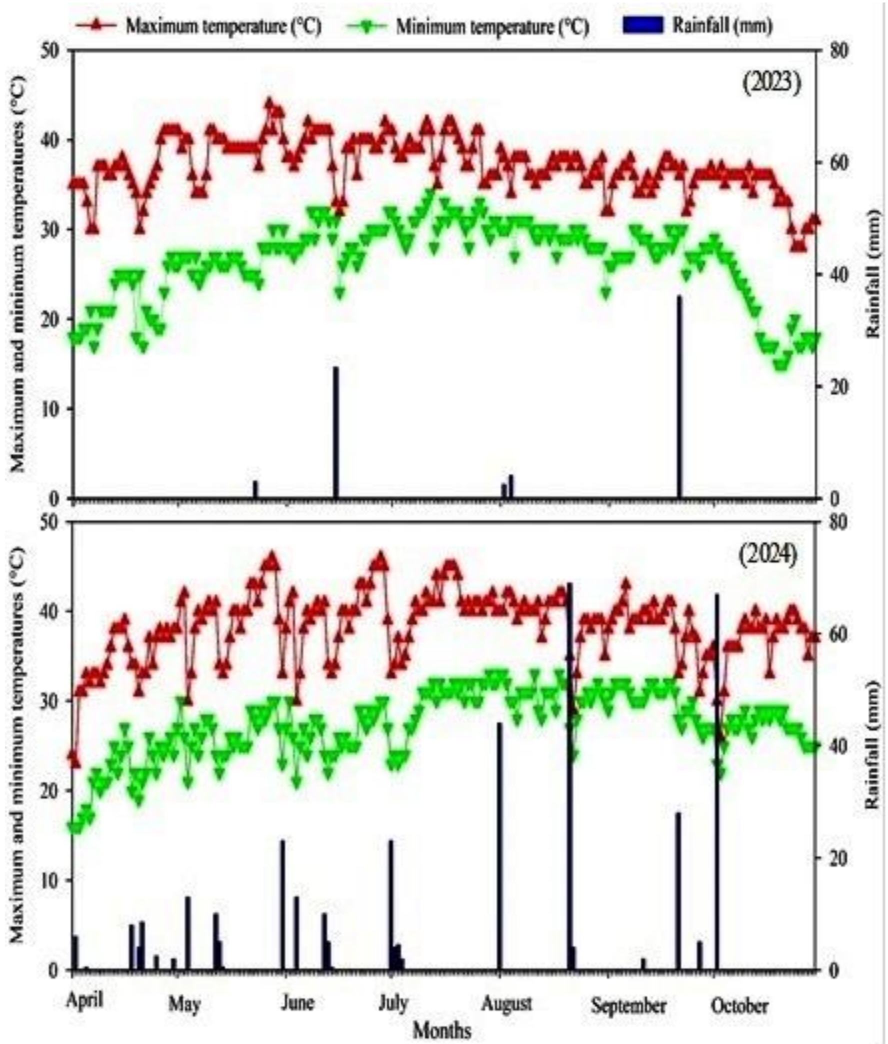

Fig. 1. Meteorological data including both daily maximum and minimum temperatures and rainfall during both growing years
(Source: Weather Observatory Agricultural Research Institute, Ratta Kulachi, Dera Ismail Khan)

Experimental design and Treatments: The current experiment was conducted for two consecutive years (2023 and 2024) by applying randomized complete block design (RCBD) with split-plot arrangement and three replications of each treatment having a net sub plot size of 10 m × 3 m. The main plots were tillage systems (a) reduced tillage (b) conventional tillage. The subplots were nutrient management treatments, (i) NPK_1 (0:0:0), (ii) NPK_2 (200:0:0), (iii) NPK_3 (0:120:0), (iv) NPK_4 (0:0:150), (v) NPK_5 (200:120:0), (vi) NPK_6 (200:0:150), (vii) NPK_7 (0:120:150), (viii) NPK_8 (200:120:150) and (ix) NPK_9 (250:170:200 kg ha^{-1}). The aforementioned treatments were applied during both the experimentation seasons.

Crop Husbandry: At first, seedbed was prepared for the cultivation of cotton with separate sub plots were prepared to compare the land preparation systems (conventional vs reduced tillage). In plots of reduced tillage, two cycles of tillage operations were performed whereas in conventional tillage plots four cycles of tillage operations were performed including disk plow, tiller and two cycles of rotavator (Fig. 2). The basal dose fertilizers including urea, triple superphosphate (TSP) and potassium sulfate (K_2SO_4) were applied at the time of land preparation. The fertilizers were applied with a hand drill which was positioned slightly in front of the seed rows at the time of sowing. The remaining split doses of N were applied to all the treatments at the specific growth stage as per the prescribed doses. Additionally, fertilizer treatments were carried out in both years according to the stated NPK rates (kg ha^{-1}) for each treatment. After application of fertilizer cotton seed (variety Bt-FH-333; Dated: April 12, 2023 and April 14, 2024) were sown using a seed drill. The process of thinning was done 20-30 days after seedling emergence to maintain the desired plant population, while irrigation was applied as per the requirement of crop. The irrigation was applied after every 5-7 days to adequately moisten crop root zone (each irrigation at the depth of 75-100 mm), however total 13-14 irrigation were applied. The agronomic practices such as weed control was carried out by spraying pendimethalin and S-metolachlor, however whitefly and jassids were controlled by spraying imidacloprid followed by pink bollworm was controlled by bifenthrin as per labelled doses. The picking of cotton bolls was carried out manually (Dated: October 20, 2023 and October 25, 2024).

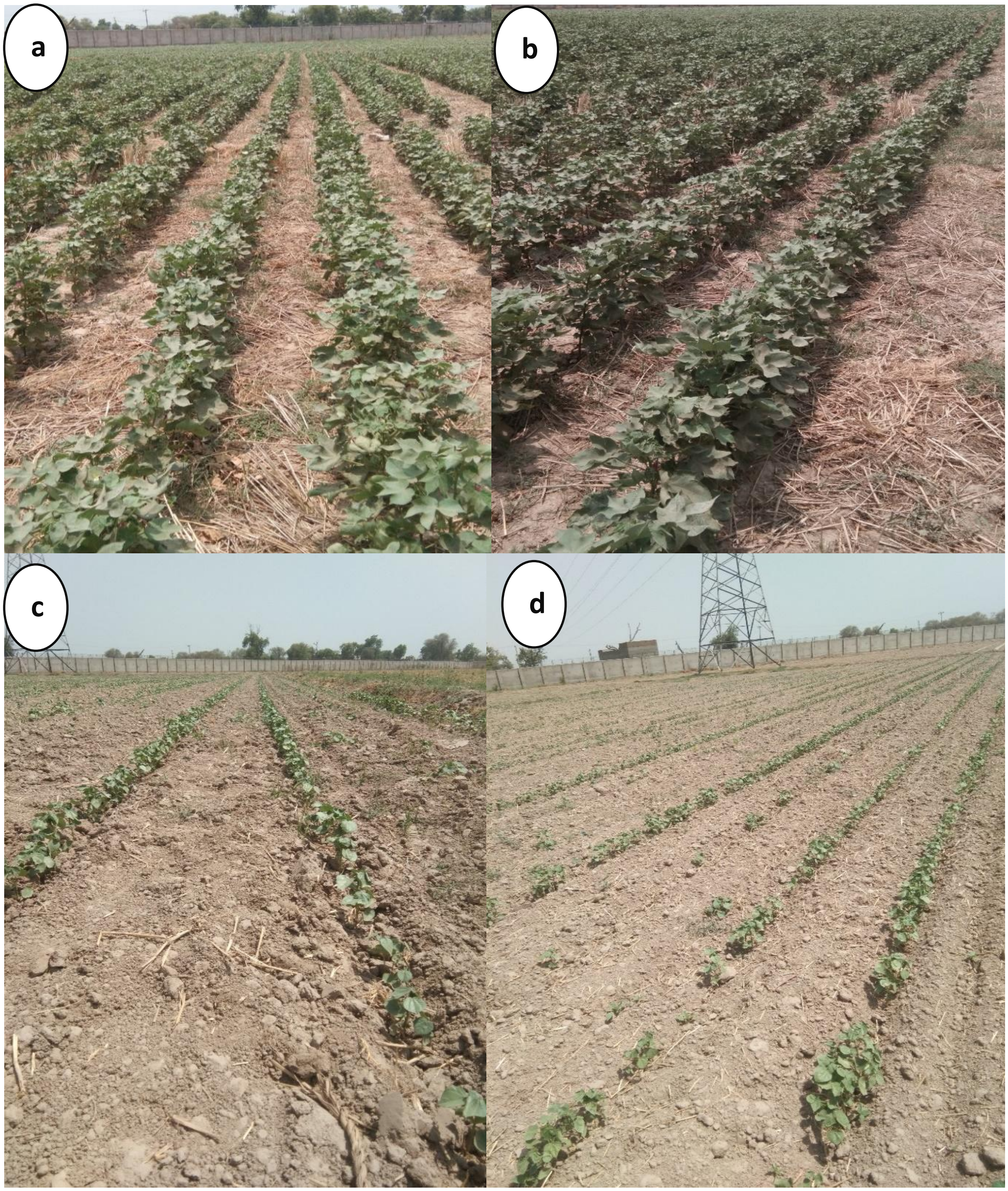

Fig. 2. Pictorial representation of field experiment. "a" and "b" are depicting reduced tillage plots while "c" and "d" are showing conventional tillage plots.

Data Collection: Data parameters involved morphological, yield and fiber quality of grown cotton during both the experimentation years. The morphological parameters included sympodial and monopodial branches were counted manually 85-90 DAS by tagging six plants in sub plot of each treatment prior to first picking. Furthermore the data was collected from tagged and mean of two plants was considered as a single replicate which further statistically analyzed. Afterwards plant height (cm) was measured at 115 DAS or at physiological maturity by using a measuring scale from the same tagged plants. The productive bolls were counted manually at the time maturity around 120 DAS. Boll weight (g) was measured on weighing balance in laboratory by picking the fully opened and healthy bolls. Afterwards lint was separated from the seed cotton and weight of 100 cotton seed (g) was measured through the digital weighing balance in the laboratory. Seed cotton yield (kg ha^{-1}) was estimated on the basis of obtained yield from the net plot area. Additionally, fiber quality attributes including fiber length (mm), fiber strength (µg $inch^{-1}$), fiber uniformity (%), micronaire value (g tex^{-1}) were analyzed using 20 g lint sample from each treatment. The fiber quality of cotton was evaluated through computerized High-Volume Instrument (HV, USTER, 900A) available at fiber testing laboratory of Central Cotton Research Institute (CCRI), Multan Pakistan. The ginning outturn was estimated by collecting 300 g of seed from each treatment followed by ginning and calculation through the equation 1.

$$Ginning\ outturn\ (\%) = \frac{Weight\ of\ lint\ (g)}{Weight\ of\ seed\ cotton\ (g)} \times 100 \qquad (1)$$

Economic analysis: Economic analysis was also performed by taking local market prices of all the major inputs and outputs prevailing during the 2023 and 2024 which further converted to current date US dollar (USD) by using the equation 2 & 3. The cost of cultivation was calculated by including expenditures on land rent, land preparation, seed, fertilizer, pesticide, labor, irrigation, cultural practices and harvesting. Gross income was estimated by cotton seed yield and market sale price, while net return was calculated by subtracting the total production cost from gross income. After that benefit cost ration (BCR) was calculated for both of the conducted experiments.

$$Net\ retun = Gross\ income - Total\ cost \qquad (2)$$

$$Benefit\ Cost\ Ratio\ (BCR) = \frac{Gross\ income}{Total\ cost} \qquad (3)$$

Statistical analysis: The recorded data were subjected to three-way analysis of variance (ANOVA) using the statistical software (Statistix 8.1). In addition the Pearson's correlation coefficient were calculated through the means of measured variables through the mix matrix correlation calculation on OriginPro V. 2025. The correlation was performed to evaluate the relationship among plant growth, yield and fiber quality attributes. The experiment was conducted as per RCBD with split-plot arrangement where factor A (tillage operations) was assigned as main plot and factor B (fertilizer doses) served as a subplot with three replications of each randomized treatment. The current trial was conducted on the same location for two consecutive years and year was included in the statistical analysis as a fixed factor. The means of treatments were compared using Tuckey's honestly significant difference (HSD) test at $p \leq 0.05$ by following the procedure described by Steel *et al*. (1997).

RESULTS

Growth and Yield Attributes of Cotton: The effect of three-way interaction of TS×NPK×Year significantly influenced the sympodial branches $plant^{-1}$ and plant height (cm) of cotton (Table 2). The statistical analysis revealed that NPK (200:120:150) dose resulted in the maximum sympodial branches (57.7 and 59.2 sympodial branches $plant^{-1}$) during 2023 and 2024 under reduced tillage. Similarly, NPK (200:120:150) outperformed under conventional tillage (59.9 and 51.9 sympodial branches $plant^{-1}$) during 2023 and 2024 under conventional tillage. The influence of interactive effect of TS×NPK×Year was found significant on plant height during both years of the experiment. Therefore, maximum plant height (151.5 cm) was attained by the application of NPK (200:120:150 kg ha^{-1}) in 2024 under reduced tillage and 150.1 cm taller plants were observed under conventional tillage in 2023 as compared to minimum plant height under control (Table 2).

The effect of all the studied factors significantly influenced the number of bolls ($plant^{-1}$), boll weight (g) and 100 seed weight (g). The maximum number of bolls $plant^{-1}$ (59.7 bolls in 2023 and 60.7 bolls in 2024) resulted by balanced NPK (200:120:150 kg ha^{-1}) under the reduced tillage condition. While the maximum bolls $plant^{-1}$ (60.0) under conventional tillage was also produced by same treatment in 2024. The maximum boll weight (4.00 g) attained by (NPK (200:120:150 kg ha^{-1}) under reduced tillage during both 2023 and 2024 as compared to the control. The highest boll weight (3.97 g) was observed in the same treatment under conventional tillage in 2023, while the boll weight in 2024 was statistically at par. The 100-cotton seed weight (10.89 and 10.29 g) was also found maximum under the application of balanced NPK (200:120:150 kg ha^{-1}) during both of year in reduced tillage treatment. Similarly, results were attained under the conventional tillage which showed that maximum seed weight (10.89 and 10.32g) was observed with non-significant influence during both the years 2023 and 2024 (Table 3).

Table 2. Effect of different tillage systems and fertilizer application rates on plant height (cm) and sympodial branches plant^{-1} of cotton

Tillage system (TS)	Fertilizer (Balanced NPK)	Plant height (cm)		Sympodial branches plant^{-1}	
		2023	2024	2023	2024
TS1	NPK1	72.5^{qr}	74.5^{o-r}	16.7^{i}	19.2^{f}
	NPK2	114.2^{kl}	116.2^{i-l}	36.6^{n}	38.5^{m}
	NPK3	93.4^{mn}	95.4^{mn}	27.9^{y}	29.9^{v}
	NPK4	78.1^{o-q}	80.2^{o}	19.9^{d}	22.0^{c}
	NPK5	137.3^{fg}	139.3^{d-g}	49.8^{f}	51.6^{d}
	NPK6	121.4^{h-j}	123.4^{h}	34.1^{p}	36.1^{o}
	NPK7	97.2^{mn}	99.2^{m}	30.3^{u}	32.3^{r}
	NPK8	149.5^{a-c}	151.5^{a}	57.7^{b}	59.2^{a}
	NPK9	144.1^{b-e}	146.1^{a-c}	46.6^{i}	49.6^{g}
TS2	NPK1	71.1^{r}	73.1^{p-r}	14.9^{j}	17.3^{h}
	NPK2	113.4^{l}	115.4^{j-l}	31.0^{t}	33.1^{q}
	NPK3	92.2^{n}	94.2^{mn}	24.7^{b}	26.7^{a}
	NPK4	77.5^{o-r}	79.6^{op}	17.7^{g}	19.7^{e}
	NPK5	136.3^{g}	138.3^{e-g}	42.8^{l}	45.0^{j}
	NPK6	120.2^{h-k}	122.2^{hi}	29.5^{w}	31.6^{s}
	NPK7	96.4^{mn}	98.4^{mn}	27.3^{z}	29.3^{x}
	NPK8	148.1^{a-c}	150.1^{ab}	49.9^{e}	51.9^{c}
	NPK9	143.5^{c-f}	145.5^{a-d}	44.0^{k}	46.9^{h}
		$p \leq 0.05$			
TS×NPK×Year		<0.001		0.046	

TS_1 = Reduced tillage; TS_2= Conventional tillage; NPK_1 = 0:0:0; NPK_2 = 200:0:0; NPK_3 = 0:120:0; NPK_4 = 0:0:150; NPK_5 =200:120:0; NPK_6 =200:0:150; NPK_7 =0:120:150; NPK_8 =200:120:150; NPK_9 =250:170:200 kg ha^{-1}.

Table 3. Effect of different tillage systems and fertilizer application rates on number of bolls plant^{-1}, mean boll weight and 100 cotton seeds weight of the cotton crop.

Tillage system	Fertilizer	Number of bolls plant^{-1}		Boll Weight (g)		100 Seed Weight (g)	
(TS)	**(NPK)**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
TS1	NPK1	15.2^{tu}	16.2st	1.0^{pq}	1.5^{l-n}	5.3^{o}	5.5^{n}
	NPK2	35.1^{jk}	36.1^{ij}	2.2^{h}	2.7^{f}	8.8^{e}	9.2^{d}
	NPK3	25.1^{op}	26.1^{m-o}	1.6^{k-m}	2.0^{i}	6.5^{j}	6.8^{i}
	NPK4	18.1^{qr}	19.1^{q}	1.1^{o}	1.6^{jk}	5.8^{m}	6.1^{l}
	NPK5	45.6^{ef}	46.6^{e}	2.9^{e}	3.4^{c}	9.1^{d}	9.5^{c}
	NPK6	38.1^{gh}	39.1^{g}	2.4^{g}	2.9^{e}	8.0^{g}	8.3^{f}
	NPK7	26.6^{l-n}	27.6^{l}	1.7^{j}	2.2^{h}	6.3^{k}	6.8^{i}
	NPK8	59.7^{ab}	60.7^{a}	4.0^{a}	4.0^{a}	10.2^{b}	10.8^{a}
	NPK9	50.1^{cd}	51.1^{c}	3.2^{d}	3.7^{b}	7.5^{h}	8.9^{e}
TS2	NPK1	14.5^{u}	15.5^{tu}	1.0^{q}	1.4^{n}	5.3^{o}	5.5^{n}
	NPK2	34.4^{k}	35.4^{jk}	2.2^{h}	2.6^{f}	8.8^{e}	9.2^{d}
	NPK3	24.4^{p}	25.4^{n-p}	1.5^{mn}	1.9^{i}	6.6^{j}	6.8^{i}
	NPK4	17.4^{rs}	18.4^{qr}	1.1^{op}	1.5^{k-m}	5.9^{m}	6.1^{l}
	NPK5	44.9^{f}	45.9^{ef}	2.8^{e}	3.3^{c}	9.1^{d}	9.5^{c}
	NPK6	37.4^{hi}	38.4^{gh}	2.3^{g}	2.8^{e}	8.1^{g}	8.3^{f}
	NPK7	25.9^{m-o}	26.9^{lm}	1.6^{j-l}	2.1^{h}	6.4^{k}	6.8^{i}
	NPK8	59.0^{b}	60.0^{ab}	3.9^{a}	3.9^{a}	10.3^{b}	10.8^{a}
	NPK9	49.4^{d}	50.4^{cd}	3.1^{d}	3.6^{b}	7.6^{h}	8.9^{e}
			$p \leq 0.05$				
TS×NPK×Year		<0.001		0.017		<0.001	

TS_1 = Reduced tillage; TS_2= Conventional tillage; NPK_1 = 0:0:0; NPK_2 = 200:0:0; NPK_3 = 0:120:0; NPK_4 = 0:0:150; NPK_5 =200:120:0; NPK_6 =200:0:150; NPK_7 =0:120:150; NPK_8 =200:120:150; NPK_9 = 250:170:200 kg ha^{-1}. Means with similar letters and having no letters are not significantly different at 0.05 probability level.

Table 4. Effect of different tillage systems and fertilizer application rates on seed cotton yield, ginning outturn and fiber length of the cotton crop

Tillage system	Fertilizer	Seed cotton yield (kg ha^{-1})		Ginning Outturn (%)	
(TS)	(NPK)	2023	2024	2023	2024
TS1	NPK1	764	814	20.5^{wx}	21.8^{vw}
	NPK2	1460	1510	39.1^{mn}	40.3^{m}
	NPK3	1030	1080	27.6^{rst}	28.9^{qr}
	NPK4	811	861	21.8^{vw}	23.1^{v}
	NPK5	1871	1921	50.0^{gh}	51.3^{g}
	NPK6	1599	1649	42.8^{jk}	44.1^{j}
	NPK7	1098	1148	29.4^{pq}	30.7^{p}
	NPK8	2646	2696	70.7^{ab}	71.9^{a}
	NPK9	2147	2197	57.4^{de}	58.7^{d}
TS2	NPK1	684	734	18.1^{y}	19.4^{xy}
	NPK2	1380	1430	36.7^{o}	37.9^{no}
	NPK3	950	1000	25.2^{u}	26.5^{tu}
	NPK4	731	781	19.4^{xy}	20.7^{wx}
	NPK5	1791	1841	47.6^{i}	48.9^{hi}
	NPK6	1519	1569	40.4^{lm}	41.7^{kl}
	NPK7	1018	1068	27.0st	28.3^{q-s}
	NPK8	2566	2616	68.3^{c}	69.5^{bc}
	NPK9	2067	2117	55.0^{f}	56.3^{ef}
$p \leq 0.05$					
TS×NPK×Year		NS		0.033	

TS_1 = Reduced tillage; TS_2= Conventional tillage; NPK_1 = 0:0:0; NPK_2 = 200:0:0; NPK_3 = 0:120:0; NPK_4 = 0:0:150; NPK_5 =200:120:0; NPK_6 =200:0:150; NPK_7 =0:120:150; NPK_8 =200:120:150; NPK_9 = 250:170:200 kg ha^{-1}. Means sharing dissimilar letters are different significantly at 0.05 probability level.

Fiber Quality Attributes: The effect of individual NPK significantly influenced fiber strength (g tex^{-1}), micronaire (µg inch^{-1}), fiber uniformity (%) and fiber length (cm). The effect of TS on fiber strength resulted maximum strength by reduced tillage (30.4 g tex^{-1} and 31.5 g tex^{-1}) during both the years 2023 and 2024 under the application of balanced NPK (200:120:150 kg ha^{-1}) followed by the highest fertilizer dose of NPK (250:170:200 kg ha^{-1}) in both seasons. The results revealed that micronaire (µg inch^{-1}) was lower under the NPK (200:120:0, 200:120:150, and 250:170:200 kg ha^{-1}) while micronaire values were higher under (0:120:150 kg ha^{-1}). Fiber uniformity increased with increasing nutrient inputs which was maximum 83.7% during 2023 while it reduced to 74.5% in 2024 by the application of NPK (250:170:200 kg ha^{-1}). The balanced NPK outperformed with a maximum fiber length in both of the years and under both tillage systems. Therefore, highest fiber length (39.5 mm in 2024 and 37.5 mm in 2023) was produced under the combination reduced tillage and the cotton from conventional tillage produced maximum fiber length (39.1 mm in 2024 and 37.1 mm in 2023) (Table 5).

Economic analysis: Substantial variations in total income, total expenditure, net benefits, and benefit-cost ratios across different tillage and nutritional regimes of NPK were observed in the economic analysis (Table 6). The reduced tillage system at NPK (200:120:150 kg ha^{-1}) showed the maximum economic returns of US $: 1003.18 ha^{-1} with the BCR of 2.3, while achieving 2803 kg ha^{-1} seed cotton yield during the present study. Contrastingly the conventional tillage system resulted lower yield and economic retunes 11-14% as compared to reduced tillage with NPK (200-120-150 kg ha^{-1}).

Table 5. Effect of different tillage systems and fertilizer application rates on fiber strength (g tex^{-1}), micronaire (µg $inch^{-1}$), fiber uniformity (%) and fiber length (cm) of the cotton crop

Tillage system	Fertilizer	Fiber Strength (g tex^{-1})		Micronaire (µg $inch^{-1}$)		Fiber Uniformity (%)		Fiber Length (mm)	
(TS)	(NPK)	2023	2024	2023	2024	2023	2024	2023	2024
TS1	NPK1	25.4	26.4	4.1	4.0	80.7	72.6	16.2	21.2
	NPK2	26.4	27.1	4.0	3.8	82.0	73.7	21.9	26.9
	NPK3	24.4	25.4	4.1	4.0	82.7	74.4	16.6	21.6
	NPK4	24.2	25.2	4.2	4.1	80.6	72.4	15.1	20.1
	NPK5	28.4	29.4	3.8	3.7	82.3	73.6	27.3	32.3
	NPK6	27.4	28.3	3.9	3.8	82.0	73.3	22.7	27.9
	NPK7	25.4	26.4	4.1	4.0	83.0	74.2	17.9	22.9
	NPK8	30.4	31.5	3.7	3.5	83.7	74.5	37.5	39.5
	NPK9	29.4	30.4	3.8	3.6	83.7	74.9	30.0	35.0
TS2	NPK1	24.6	25.6	4.0	3.9	80.7	72.7	15.8	20.8
	NPK2	25.6	26.7	3.9	3.7	82.0	73.8	21.5	26.5
	NPK3	23.6	24.6	4.0	3.8	82.7	74.5	16.2	21.2
	NPK4	23.4	24.4	4.1	3.9	80.6	72.5	14.7	19.7
	NPK5	27.6	28.6	3.4	3.6	82.3	73.7	26.9	31.9
	NPK6	26.6	27.9	3.8	3.7	82.0	73.4	22.3	27.5
	NPK7	24.6	25.6	4.0	3.8	83.0	74.3	17.5	22.5
	NPK8	29.6	30.6	3.7	3.5	83.3	74.6	37.1	39.1
	NPK9	28.6	29.2	3.6	3.5	83.7	75.0	29.6	34.6
$p \leq 0.05$									
TS×NPK×Year		NS		NS		NS		NS	

Table 6. Effect of tillage practices and NPK levels on cotton economics (means of 2023 & 2024).

Treatments	NPK levels	Seed cotton yield (kg ha^{-1})	Total income (US \$. ha^{-1})	Expenditure (US \$. ha^{-1})	Net benefit (US \$. ha^{-1})	Benefit cost ratio (BCR)
TS_1	NPK_1	820	644.21	357.89	293.47	1.8
	NPK_2	1764	1387.92	631.33	631.33	2.2
	NPK_3	1211	977.77	433.41	433.41	2.3
	NPK_4	844	700.76	393.68	302.06	1.8
	NPK_5	1990	1567.58	712.21	712.21	2.2
	NPK_6	1701	1324.93	608.78	608.78	2.2
	NPK_7	1130	912.63	411.58	404.42	2.2
	NPK_8	2803	2185.31	966.32	1003.18	2.3
	NPK_9	2138	1691.41	765.18	765.18	2.2
TS_2	NPK_1	679	579.07	368.63	243.01	1.6
	NPK_2	1126	934.82	642.06	402.99	1.5
	NPK_3	819	700.76	444.15	293.12	1.6
	NPK_4	747	634.91	404.42	267.35	1.6
	NPK_5	1722	1379.33	722.95	616.30	1.9
	NPK_6	1467	1161.01	619.52	525.03	1.9
	NPK_7	1037	849.64	422.32	371.14	2.0
	NPK_8	2460	1943.37	977.05	880.42	2.0
	NPK_9	2126	1735.79	1002.11	760.88	1.7

TS_1 = Reduced tillage; TS_2= Conventional tillage; NPK_1 = 0:0:0; NPK_2 = 200:0:0; NPK_3 = 0:120:0; NPK_4 = 0:0:150; NPK_5 =200:120:0; NPK_6 =200:0:150; NPK_7 =0:120:150; NPK_8 =200:120:150; NPK_9 =250:170:200 kg ha^{-1}.

Correlation Analysis: The mix matrix correlation analysis were based on the means of treatments which resulted higher values of correlation due to reduced variation within the treatments. The correlation analysis of trial conducted in 2023 revealed that all the parameters were positively associated with each other, however correlation pattern suggest that trait related to reproductive and vegetative growth imposed a combined effect to attain a better yield. A strong positive correlation 0.710-0.91 was observed among PHM, NBP and MBW which exhibited a strong relation with GOT, FL, SCY and FS which indicate a strong correlation among growth yield and fiber quality attributes. While the correlation results of trial conducted during 2024 represented that growth, yield and fiber quality parameters were positively linked to each other. The correlation pattern suggested a strong correlation among PHM, MBW, GOT, FL, FU, FS and SCY (0.90-0.99). The correlation of second year trial demonstrated the improvement in boll development and growth attributes of cotton which improved the seed cotton yield and fiber performance as compared the first year of study. Contrastingly NBP showed a weak association with almost all the studied parameters (Table 7).

Table 7. Mix scatter plot of growth, yield and fiber quality attributes of cotton cultivated during 2023 and 2024

	PHM		NBP		MBW		SCY		GOT		FL		FS		FU	
	2023	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
PHM			0.99	0.23	0.98	1.00	0.97	0.97	0.97	0.97	0.94	0.94	0.94	0.94	0.73	0.66
NBP	0.99	0.23			1.00	0.18	0.99	0.12	0.99	0.12	0.97	0.02	0.95	0.07	0.73	0.30
MBW	0.98	1.00	0.99	0.18			0.99	0.98	0.99	0.98	0.99	0.96	0.96	0.96	0.71	0.65
SCY	0.97	0.97	0.99	0.12	0.99	0.98			0.99	0.99	0.99	0.99	0.97	0.97	0.69	0.63
GOT	0.97	0.97	0.99	0.12	0.99	0.98	0.99	1.00			0.99	0.99	0.97	0.97	0.69	0.63
FL	0.94	0.94	0.97	0.02	0.99	0.96	0.99	0.99	0.99	0.99			0.97	0.97	0.65	0.58
FS	0.94	0.94	0.95	0.07	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97			0.61	0.53
FU	0.73	0.66	0.72	0.30	0.71	0.65	0.69	0.63	0.69	0.63	0.65	0.58	0.61	0.53		

Whereas; PHM=Plant height at maturity, NBP= Number of bolls plant^{-1}, MBW=Mean boll weight (g), SCY=Seed cotton yield (kg ha^{-1}), GOT=Ginning out turn (%), FL=Fiber length (mm), FS=Fiber strength (g tex^{-1}), FU=Fiber uniformity (%)

DISCUSSION

The application of NPK fertilizer coupled with TS significantly influenced the growth, yield and fiber quality of cotton which is validated by a second-year experiment. The contrasting result could also be attributed to other research factors as our research involved the nutrient management which is also correlated to the fluctuation in the cotton growth, physiology and yield (Gwathmey *et al*., 2010; Bekele, 2020). In our research nutrient management outperformed as emergence of cotton was optimum at a balanced fertilization of NPK (200:120:150 kg ha^{-1}). The findings are strongly aligned with the fact that balanced supply of nutrients during initial growth stages of crop plays a significant role during the early stages (Xiao and Yin, 2019; Nwachukwu *et al*., 2024). The findings revealed that reduced tillage significantly improved the number of sympodial branches plant^{-1} which might be attributed due to improved soil moisture content and reduced disturbance of soil that also enhance soil quality (Singh *et al*., 2023). Furthermore, conservation tillage practices are widely reported to improve soil structure, increase OMC and microbial communities which facilitate a better nutrient efficiency and root development. The attained results strongly aligned with the findings of Pendke *et al.* (2025). Additionally, reduced tillage also improves soil quality and the soil available nutrient resources for a better growth of cotton.

The results of our study also revealed that balanced NPK (200:120:150 kg ha^{-1}) resulted in the maximum number of sympodial branches plant^{-1} during both the years 2023 and 2024. Hence, application of balanced nutrition improves nutrient use efficiency (NUE), photosynthetic efficiency of crop and assimilate the partitioning of nutrient which promote the initiation and development of more sympodial branches in the cotton (Zhou *et al*., 2023; Alagarswamy *et al*., 2024). The increase in sympodial branches likely to increase the fruit bearing branches that ultimately increase the number of bolls per plants which we observed during the both years of research under reduced tillage and balanced nutrient management. The findings of our research are consistent with Boincean and Dent (2019) who reported that more boll bearing branches appear after the application of balanced NPK. The tillage practices had non-significant effect on plant height, while balanced fertilization (200:120:150 kg ha^{-1}) again outperformed with a maximum plant height during both the experimental years. The higher plant height may be attributed to the higher uptake of N which is relatively a good source for vegetative growth of cotton and promote higher photosynthesis. The findings strongly agrees with the scientific fact that height of cotton plants increased with more balanced NPK fertilizers due to higher nutrient uptake and photosynthetic activity (Zhang *et al*., 2024). In contrasting tillage systems did not significantly affect the number of bolls plant^{-1}, mean weight of boll and weight of 100 cotton seeds in either year of the study. The lack of significance could be attributed to the difference in moisture and nutrient availability during the reproductive stage under conventional and reduced system. The literature also report that reduce tillage cutoff the moisture and nutrient at early growth stages which later on create a clear difference among the reproductive traits of cotton (Pearsons *et al*., 2023). Contrastingly there was a positive nutrient management effect on the number of bolls plant^{-1} and the average weight of bolls. Among all the nutrient treatments, the highest no. of bolls and boll weight were associated with the balanced NPK (200:120:150 kg ha^{-1}) which possibly contributed to the yield increase. The highest number of bolls plant^{-1} was recorded in 2024 which was likely due to the improved weather in 2024 compared to 2023. The higher number of bolls plant^{-1} might be associated with the favorable thermo-moisture regime during the reproductive phase especially temperature near to the optimum range for cotton flowering and boll formation (28° to 32° C) and reduce stress which can improve viability of pollen, fertilization assimilate supply and the boll retention while reducing the boll shedding (Saini *et al*., 2023). These results strongly aligned with Pittelkow *et al*. (2015) who reported the positive influence of optimized weather conditions on the improvement of length of cropping season. The improvement in reproductive phase leads to improve the seed weight which ends up with a better yield (Francaviglia *et al*., 2023). Among different tillage systems, seed cotton yield and ginning outturn were impacted with reduced tillage yielding better results than conventional tillage. These findings correspond with Mrabet *et al*. (2024), who attributed the increased yield under reduced tillage to better soil moisture contents, water holding capacity and improved OM. The results of our study revealed that changes in nutrient regimes in combination with reduced tillage resulted in different ginning outturns and fiber lengths (Zhou *et al*., 2026). The 200:120:150 kg ha^{-1} NPK treatment had the highest ginning outturn with balanced fertilization improving ginning quality. The treatments with 200:120:150 and 250:170:200 kg ha^{-1} NPK had the greatest fiber lengths, supporting Shah *et al*. (2022) statement of the role P in improving the fiber length by enhancing the energy metabolism of the fiber developing cells. Reduced tillage practices annually strengthened fiber with each year as reported by Wang *et al*. (2024) who stated that conservation tillage encourages further fiber strengthening and boll development. Each year, fiber strength improved, likely due to variations in climate and the influence of nutrients in the soil, as discussed by Ghaffar *et al*. (2020). In contrast, tillage practices impacted micronaire size and fiber uniformity. The strongest fibers were produced at a balanced NPK level (200:120:150 kg ha^{-1}) and at the highest fertilizer level (250:170:200 kg ha^{-1}) in the both growing seasons. These findings were aligned with the results of Boquet *et al*. (2004) and Bednarz *et al*. (2006) who also reported that proper management of fertilizers with optimum pairs of different nutrient give higher yield of any cropping system combining with conservation tillage practices. The improvement in the growth, yield and fiber quality of cotton attributed to the significance of balanced nutrient supply which ensure that plant do not face any nutritional deficiency that can limit the growth of cotton and also improve the nutrient retention within plants (Ul-Allah *et al*., 2021; Iftikhar *et al*., 2025). The economic analysis also revealed that outperforming NPK treatment in combination with reduced tillage is economically feasible in developing countries like Pakistan, however the validity of economic returns has already reported by Vinayak *et al*. (2023) and Iqbal *et al*. (2025).

Conclusion: Results revealed that integration of reduced tillage with balanced NPK fertilization progressively enhanced crop productivity, fiber quality traits, and profit of cotton crop under arid climate. Conventional tillage produced 15-18% lower seed cotton yield as compared to reduced tillage during both seasons of the experiment. Among the fertilization regimes, 200:120:150 NPK kg ha^{-1} was the most effective pair of NPK in producing highest seed cotton yield 2606-2656 kg ha^{-1} by enhancing the yielding parameters such as no. of sympodial branches per plant, boll weight, ginning outturn, and improving fiber traits quality, strength, length, and uniformity. Highest net return US $: 1003.18 ha^{-1} with the BCR of 2.3 were achieved with the combination of reduced tillage and 200:120:150 kg ha^{-1} in comparison to all other NPK combinations. Therefore, based on the results of two growing seasons at the experimental site in Dera Ismail Khan which belong to arid region, it is concluded that reduced tillage and NPK (200:120:150 kg ha^{-1}) improved cotton productivity and it can be recommended for the agroecological conditions similar to the experimental site. However, addition multi location studies are required to validate the results of current funding. Future research and efforts should be aligned with the long term reduced tillage operations to improve soil health, crop productivity and food security under different agro-climatic conditions.

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