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Research Article

IMPROVING NITROGEN USE EFFICIENCY AND FIBER QUALITY OF COTTON THROUGH COMMERCIAL VALUE ADDED FERTILIZER

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Abstract

Nitrogen (N) plays a crucial role in the growth and physiological functions of plants. However, it has been observed that plants typically utilize less than 50% of the applied nitrogen fertilizer, while the remaining nitrogen is lost from the system through processes like leaching, denitrification, and ammonia volatilization, thus impacting nitrogen use efficiency (NUE) in cotton. To address this issue, there has been a recent introduction of commercially available value-added fertilizers aimed at increasing NUE. In this context, a field experiment was conducted in 2021 at the Latif experimental farm of Sindh Agriculture University, Tando Jam, Pakistan to assess the effects of a specific value-added fertilizer, Zarkhez Plus, on cotton fiber quality. The experiment included seven different treatments with three replications, following a randomized complete block design. The treatments were as follows: T1 represented standard farming practice with urea, DAP, and MOP fertilizers; T2 included the standard farming practice with the addition of Zingro and Zoron; T3 consisted of 100% Zarkhez Green Plus along with 100% standard urea; T4 comprised 80% Zarkhez Green Plus, 100% standard urea, and Zingro and Zoron; T5 involved 100% Zarkhez Green Plus, 100% standard urea, and Zingro and Zoron; T6 included 100% Zarkhez Green Plus, 75% standard urea, and Zingro and Zoron; and T7 consisted of 100% Zarkhez Green Plus, 50% standard urea, and Zingro and Zoron. The results of the experiment revealed that Zarkhez Plus significantly enhanced and about 10% increase in various plant growth parameters such as plant height, number of buds, flowers, bolls, opened/closed bolls, root biomass, and seed cotton yield compared to the other treatments. Additionally, quality parameters including staple length, micronaire, fiber length, and 10-12 increase in NUE were improved by the application of Zarkhez Plus. Moreover, it was observed that with the application of ZKZ Plus, 25% of the standard urea could be saved, while also positively affecting soil quality, although further assessment is needed in this regard. Overall, Zarkhez Plus demonstrated potential as a value-added fertilizer for enhancing cotton yield, fiber quality, and NUE.

Keywords: *Zarkhez plus, Nitrogen, Cotton Fiber quality, Yield, Soil Health*.

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1. Introduction

The nutritional requirements of plants are primarily fulfilled by nitrogen (N), phosphorus (P), and potassium (K), which are essential elements. However, if inorganic fertilizers are extensively applied to arable lands without adequate knowledge of the nutrient status, it can lead to a deterioration in soil health (Akande *et al*., 2010). Continuous cropping in tropical and subtropical regions results in a decline in soil nutrient levels and disrupts soil microorganism functioning

(ECA, 2001). Consequently, crop productivity decreases, and overall resources available to farmers diminish (FAO, 2006). This situation has significant environmental consequences as the excessive use of inorganic fertilizers raises environmental concerns and disrupts soil health (Shiyam and Binang, 2011).

Nitrogen (N) is a critical nutrient that plays a vital role in enhancing crop production (Sutton *et al*., 2019). Compared to other essential nutrients, plants require nitrogen in larger quantities (Iqbal *et al*., 2020). It serves as a primary component of amino acids, which are fundamental building blocks of proteins and enzymes. Nitrogen is also a crucial component of the chlorophyll molecule, playing a significant role in photosynthesis (Chen *et al*., 2021). Agricultural soils and cropping systems worldwide often lack sufficient nitrogen, necessitating the application of external nitrogen inputs through fertilizers to improve crop yield (Mohan *et al*., 2015). In cotton production, there is often insufficient nitrogen available, resulting in a significant loss of applied nitrogen (Ahmed *et al*., 2017; Khan *et al*., 2017). Moreover, this inadequate application contributes to pollution of ground and surface waters due to nitrate leaching (Vitousek *et al*., 2009). Over-application of nitrogen fertilizer in cotton can lead to "rank growth" and fruit shedding, ultimately reducing yields (Ahmed *et al*., 2017; Khan *et al*., 2017). Thus, improper application of nitrogen fertilizers has adverse environmental impacts, including accelerated global warming through increased ammonia volatilization and nitrous oxide emissions.

In Pakistan, modern farming practices heavily rely on chemical fertilizers, particularly nitrogen fertilizers (Lal, 2018). Despite being one of the top four countries in nitrogen consumption, the nitrogen use efficiency (NUE) in Pakistan's agricultural system is low, resulting in the lowest average crop yields and the highest nitrogen application rates. On the other hand, more than 50% of the applied nitrogen in soils is usually lost to the environment in terms of ammonia (NH3) volatilization, nitrous oxide (N2O) emissions, and nitrate (NO3) leaching (Tufail *et al*., 2024). Globally, approximately 190 million tons of chemical fertilizers were consumed in 2018, with nitrogen accounting for about 58% of the total, followed by phosphorus (22%) and potassium (20%) (FAO, 2020). In Pakistan, the local manufacturing capacity for urea, a nitrogen-based fertilizer, is estimated to be around 7 million tons per year, while the average demand for urea ranges between 5.5-5.9 million tons per year (Engro, 2019).

Nitrogen fertilizers have proven to be an effective method for enhancing crop productivity over the past five decades. However, with the growing global population, there is an urgent need to improve nitrogen use efficiency (NUE) and explore innovative and cost-effective solutions to meet plant nitrogen requirements. The quantity of nitrogen fertilizer used worldwide has reached such high levels that it is now comparable to the natural nitrogen fixation process from the atmosphere into the bio-lithosphere on a global scale (Steffen *et al*., 2015; Zhang *et al*., 2015). Organic fertilizers alone are insufficient to meet the nutritional requirements of large areas due to limited availability, inconsistent nutrient content, and the need for extensive labor. To enhance soil health, a combination of inorganic and organic manures has been employed (Akande *et al*., 2010). The use of both organic and chemical fertilizers improves soil pH, increases soil carbon levels, enhances soil fertility, and ultimately boosts crop yield (Rautaray *et al*., 2003). Further, the application of N rate enhanced, soil N content, cotton dry matter weight, seed cotton

yield, and physiological parameters also improved (Ma *et al*., 2025).

The application of N fertilizers has a significant positive economic impact on cotton, influencing its growth, boll development, lint yield, and fiber quality (Luo *et al*., 2018). Managing nitrogen in cotton cultivation can be challenging due to the unique characteristics of cotton plants, which have indeterminate growth habits (Munir *et al*., 2015). Inadequate nitrogen fertilization can hinder cotton development and growth, leading to reduced yield (Yang *et al*., 2011). Conversely, excessive nitrogen fertilization rates can decrease boll production due to excessive vegetation growth. Optimal nitrogen levels have been found to enhance photosynthetic capability, increase leaf area, plant height, node quantity, and improve fiber quality (Chen *et al*., 2020). Therefore, nitrogen is considered one of the key factors in cotton production (Yang *et al*., 2021). Nitrogen fertilizers have also been observed to significantly impact the morphology and fiber quality of cotton (Chen *et al*., 2019; Vendar, 2022), as well as the production of physiologically active substances, overall growth, and seed cotton yield (Rochester and Constable, 2020).

Achieving greater nitrogen use efficiency and increased crop production is attainable by utilizing slow-release nitrogen fertilizers (Hawkesford, 2014; Zhang *et al*., 2015; Rajput, 2021). These fertilizers release nitrogen gradually, providing a more controlled and efficient supply to plants. In summary, while nitrogen fertilizers have been effective in boosting crop productivity, the need to enhance nitrogen use efficiency has become crucial due to population growth. The excessive use of nitrogen fertilizers globally necessitates the exploration of innovative solutions. It is encouraging to know that the decline in nitrogen use efficiency can be addressed, and the use of slow-release nitrogen fertilizers offers a promising approach to improve both nitrogen use efficiency and crop production.

Zarkhez (ZKZ) Plus is an innovative chemical fertilizer that possesses soil conditioning and bio-stimulation properties, along with an organic filler. These unique characteristics of ZKZ Plus have the potential to enhance nitrogen utilization compared to conventional urea fertilizer. Furthermore, reports indicate that the use of ZKZ Plus fertilizer has resulted in a yield increase of approximately 10-12% (Keerio et al., 2022). Moreover, these products have the potential to enhance soil moisture content and improve soil health (Keerio *et al*., 2022). The cotton crop plays a crucial role in the economy of Pakistan, contributing around 0.8% to the overall GDP and approximately 4.5% in value addition to the agriculture sector (Rehman *et al*., 2019). The ZKZ Plus, a value-added fertilizer, contains organic fillers and bio-stimulants that prolong the availability of nutrients, resulting in increased cotton yield and improved quality. It is specifically designed to enhance the yield and quality of all crops, by improving nitrogen use efficiency through the balanced proportions of three major nutrients: nitrogen, phosphorus, and potassium (Engro, 2019). Given the significance of ZKZ Plus in enhancing NUE in cotton, this study was designed with the following objectives:

(i) To examine the impact of value-added fertilizers on cotton yield and (ii) the evaluate the influence of value-added fertilizers on nitrogen use efficiency in cotton.

2. MATERIALS AND METHODS

A field experiment was conducted at the research farm of Latif Experimental Farm, Sindh Agriculture University, Tando Jam, Pakistan, to examine the impact of value-added fertilizers on nitrogen use efficiency and cotton quality. The experimental site is situated at a latitude of 25.676521 and a longitude of 68.762361, falling within a

semi-arid climate characterized by dry cool winters and hot summers.

Prior to the experiment, the soil at the site was analyzed. The soil of study is area typically alluvial nature and majority of soil study. The results revealed that the soil texture was classified as clay loam, according to the Soil Survey of Pakistan, the soil of Latif Experimental Farm Tandojam, belongs to the Pacca soil series. Pacca soil series are a type of alluvial sediments that originated from the Indus River and its tributaries. The pH of the soil was 7.5, indicating a slightly alkaline nature. The electrical conductivity of the soil extract (ECe) was 0.36 dSm-1, suggesting a moderate level of salinity. The soil's organic matter content was found 0.43%, while the total nitrogen content was 0.02%. Additionally, the soil's saturation percentage was 30%, indicating the proportion of the soil's pore spaces occupied by water.

2.1 Experimental layout and crops husbandry

The experiment utilized standard urea (containing 46% nitrogen), diammonium phosphate (DAP, containing 46% phosphorus pentoxide and 18% nitrogen), and muriate of potassium (MOP, containing 60% potassium oxide) as the conventional fertilizers. The value-added fertilizer Zarkhez Plus (ZKZ) was also used, which had an NPK ratio of 8-23-18 (nitrogen, phosphorus pentoxide, and potassium oxide percentages, respectively). Additionally, ZKZ contained zingro as a zinc source (33% zinc) and zoron as a boron source (20% boron).

The fertilizers were applied according to the following treatment combinations: T1: Farming Practice (standard urea + DAP + MOP) T2: Farming Practice + Zingro + Zoron T3: 100% Zarkhez Plus + 100% standard urea T4: 80% Zarkhez Plus + Zingro + Zoron + 100% standard urea T5: 100% Zarkhez Plus + Zingro + Zoron + 100% standard urea T6: 100% Zarkhez Plus + Zingro + Zoron + 75% standard urea T7: 100% Zarkhez Plus + Zingro + Zoron + 50% standard urea. The DAP and Zarkhez Plus fertilizers were applied as basal fertilizers, meaning they were incorporated into the soil before planting. Urea, on the other hand, was applied in three splits: first after 7 days of planting, then at the flowering stage, and finally before the first picking stage. Furthermore, zingro and zoron were applied at the time of the first application of urea.

For the experiment, delinted seeds of the cotton variety FH-142 were used, and the plot size for each replication was 13 m × 10 m. The experimental design followed a randomized complete block design (RCBD), and data pertaining to agronomic parameters such as ten (10) plants were selected from each treatment to observe plant height, No of buds per plant, No of flowers per plant, No. of bolls per plant, number of opened bolls per plant, root biomass and total yield and chemical parameters such as Staple length (mm), micronaire (ug inch-1), fiber strength (G tex-1) (HVI Mode), and uniform index (%) were recorded with the help of USTER HVI 1000 at Central Cotton Research Institute Sakrand (CCRIS).

2.2 Collection of plant samples and analysis

For the analysis of nitrogen content in the cotton plant, ten to twenty leaves per plot were collected from the field and transported to the laboratory (Vitale *et al*., 2014). The leaves were cleaned, washed, and subsequently dried in an oven at a temperature of 68°C for three days. After drying, the leaves were ground using a Willey Mill (Thomas Model 4) to facilitate further analysis. The nitrogen content in the plant was determined using the Kjeldahl method, as described by Ryan *et al*., (2001).

The physiological nitrogen efficiency PNE (%) = (Grain yield / Total plant N uptake) × 100 and apparent nitrogen recovery efficiency ANR (%) (N uptake in fertilized plot - N uptake in unfertilized plot) / N

applied) × 100 were calculated using formulas provided by Baligar *et al*., (2001). These efficiency measures were utilized to evaluate the utilization and recovery of N.

2.3 STATISTICAL ANALYSIS

The collected data were subjected to statistical analysis using the software Statistic 8.1. To compare the means of the treatments, a Least Significance Difference (LSD) test was performed at a 5% probability level, following the methodology described by Steel *et al*. (1997).

3. RESULT

3.1. Plant height and No of buds per plant and No of open bolls

The application of ZKZ plus in the analysis of variance resulted in increased plant height across all treatments compared to the control. Among the treatments, the highest level of ZKZ plus exhibited the greatest increase in plant height, with measurements of 144.40 cm in T5 and 136.63 cm in T6, in contrast to the control group's height of 114.49 cm (Table 1). Additionally, the use of ZKZ plus

Table: 1. Effect of Zarkhez plus fertilizers on plant height, No of buds, No of flowers, No of open bolls, root biomass.

Treatments	Plant height (cm)	No of Buds per plant	No of Flowers	No of Bolls	No of open Bolls	Root biomass (g)
T_1	114. 49 g	22.6 f	19.80 g	34.47 f	19.30 g	40.00 d
T_2	139.79 d	24.33 d	21.13 d	31.37 c	18.67 d	46.00 b
T_3	126.37 f	21.07 e	21.20 f	38.27 e	21.90 f	49.33 b
T_4	136.84 c	23.40 c	23.33 c	44.37 c	26.27 c	33.67 b
T_5	144.40 a	24.27 a	28.80 a	47.13 a	27.57 a	56.67 a
T_6	133.83 b	22.60 b	24.20 b	45.10 b	27.50 b	53.68 a
T_7	131.37 e	22.40 e	15.73 e	34.73 d	18.37 e	25.33 c

T1: Farming Practice (Standard urea + DAP + MOP) T2: Farming Practice + Zingro + Zoron T3: 100% Zarkhez (ZKZ) plus + 100% std. urea T4: 80% ZKZ plus + Zingro + Zoron + 100% std. urea T5: 100% ZKZ plus + Zingro + Zoron + 100% std. urea T6: 100% ZKZ plus + Zingro + Zoron + 75% std. urea T7: 100% ZKZ plus + Zingro + Zoron + 50% std. urea.

Treatments	Staple length (mm)	Micronaire (ug inch^{-1})	Fiber Strength (G tex^{-1}) (HVI Mode)	Uniform Index (%)
T1	22.67 e	3.60 c	24.47 c	79.60 f
T2	25.43 bc	4.30 b	27.67e	81.80 d
T3	23.40 de	3.30 c	26.70 d	81.47 d
T4	26.33 bc	4.57 b	28.37 b	82.20 c
T5	28.70 a	5.33 a	29.87 a	87.77 a
T6	27.23 ab	4.63 b	28.87 b	83.53 b
T7	24.70 cde	3.80 c	27.30 c	80.47 e

Table: 2. Effect of Zarkhez plus fertilizers on fiber quality of cotton.

T1: Farming Practice (Standard urea + DAP + MOP) T2: Farming Practice + Zingro + Zoron T3: 100% Zarkhez (ZKZ) plus + 100% std. urea T4: 80% ZKZ plus + Zingro + Zoron + 100% std. urea T5: 100% ZKZ plus + Zingro + Zoron + 100% std. urea T6: 100% ZKZ plus + Zingro + Zoron + 75% std. urea T7: 100% ZKZ plus + Zingro + Zoron + 50% std. urea.

significantly enhanced the plant height by 10% when ZKZ, Zoron, and Zingro were combined with a 100% urea dose, compared to the control group. Beyond the effect on

plant height, ZKZ plus also had a significant positive impact on the number of buds, the number of open bolls, and the number of bolls, all of which exhibited substantial increases when compared to the control group.

T1: Farming Practice (Standard urea + DAP + MOP)
T2: Farming Practice + Zingro + Zoron
T3: 100% Zarkhez (ZKZ) plus + 100% std. urea
T4: 80% ZKZ plus + Zingro + Zoron + 100% std. urea
T5: 100% ZKZ plus + Zingro + Zoron + 100% std. urea
T6: 100% ZKZ plus + Zingro + Zoron + 75% std. urea
T7: 100% ZKZ plus + Zingro + Zoron + 50% std. urea.

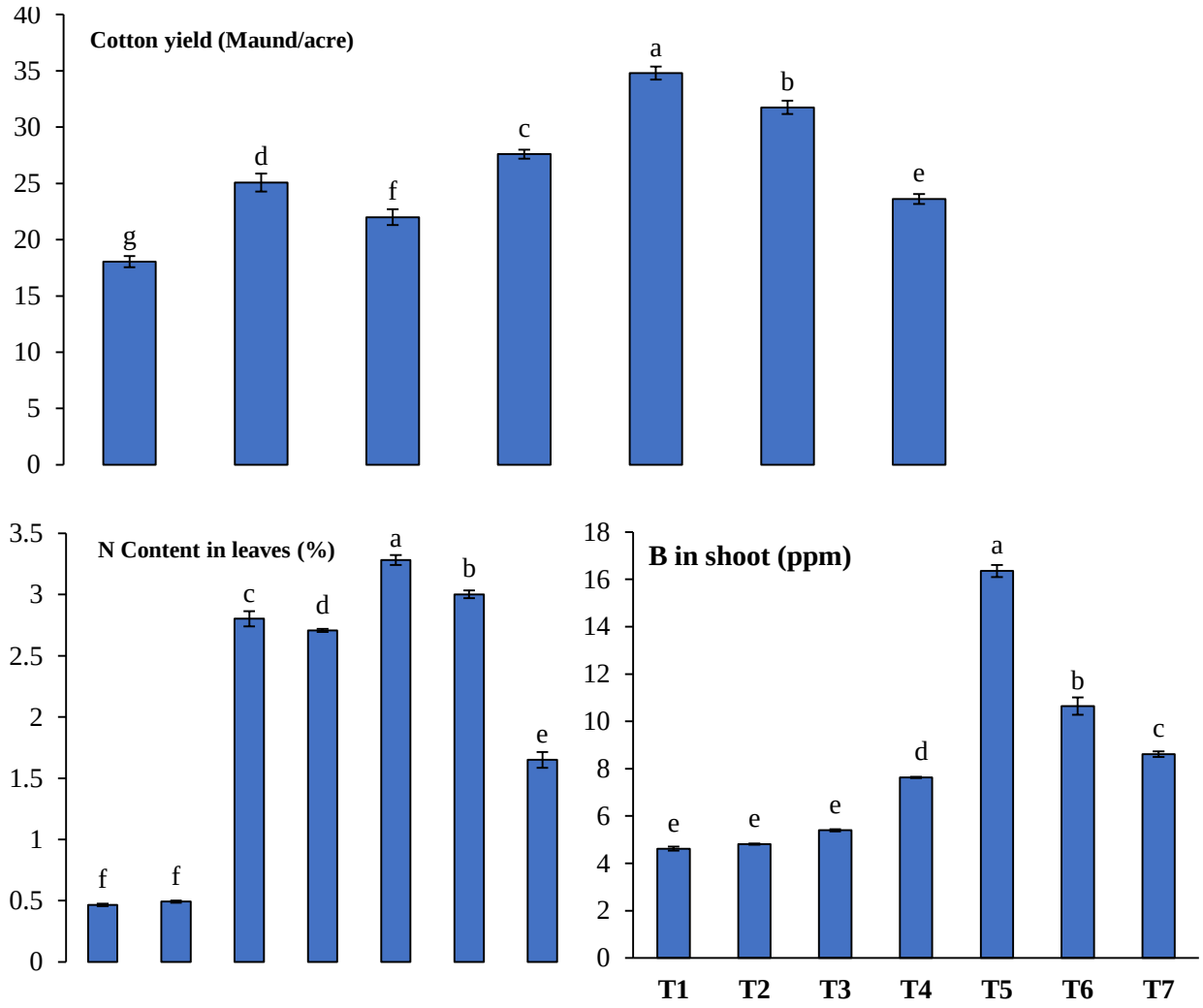

Figure 1. Effect of ZKZ plus on cotton yield, N and B contents in shoot. T1: Farming Practice (Standard urea + DAP + MOP) T2: Farming Practice + Zingro + Zoron T3: 100% Zarkhez (ZKZ) plus + 100% std. urea T4: 80% ZKZ plus + Zingro + Zoron + 100% std. urea T5: 100% ZKZ plus + Zingro + Zoron + 100% std. urea T6: 100% ZKZ plus + Zingro + Zoron + 75% std. urea T7: 100% ZKZ plus + Zingro + Zoron + 50% std. urea. Column shows means of four replications while bars show standard error. Means sharing the similar letter (s) do not differ significantly at P≤ 0.05 according to LSD test.

Additionally, the use of ZKZ plus significantly enhanced the plant height by 10% when ZKZ, Zoron, and Zingro were combined with a 100% urea dose, compared to the control. Beyond the effect on plant height, ZKZ plus also had a significant positive impact on the number of buds, the number of open bolls, and the number of bolls, all of which exhibited substantial increases when compared to the control group.

3.2. Cotton Yield and total root biomass

The application of ZKZ plus, in combination with Zoron and Zingro with a 100% urea dosage, resulted in the highest recorded yield and total root biomass in the cotton crop. In particular, ZKZ plus significantly increased the cotton yield, with measurements of 34.8 Maunds $acre^{-1}$ in T5 and 31.75 Maunds $acre^{-1}$ in T6, compared to the control (18.05 Maunds $acre^{-1}$). The same trends were observed for total root biomass, indicating that ZKZ plus not only improved the yield but also enhanced the overall biomass of the roots in the cotton crop (Table 1 and Fig. 1).

3.3. Minerals concentrations in shoots of cotton crop

The application of ZKZ plus as a NPK fertilizers had a significant positive impact on the cotton yield and nutrient content in the cotton crop. The application of ZKZ plus at the highest rate led to an increase in the N concentration in the shoots of cotton across all treatments, but notably higher N concentration was observed in T5 (3.24%) and T6 (3.0%) compared to the control group (0.46%). Additionally, ZKZ plus enhanced the N concentration in T4 (2.70%) and T3 (2.80%) compared to the control, although not to the same extent as in T5 and T6. Furthermore, apart from N, ZKZ plus also resulted in increased concentration of macro and micronutrients, specifically boron (B), in the cotton shoot. The analysis of variance indicated that the application of ZKZ plus provided the maximum concentration of B. The greatest concentration of B in the shoot was found in T5 (16.25 ppm) and T6 (10.46 ppm) in comparison to the control group (4.62 ppm).

3.4. Quality parameters of cotton fiber

The The significant role of ZKZ plus was observed in all measured fibre quality parameters of cotton including staple length, micronaire, fiber strength, uniformity index. Specifically, T5 (100% ZKZ plus + zingro + zoron + 100% Std. urea) yielded the longest staple length (28.70 mm), highest micronaire value (5.33 µg inch-1), greatest fiber strength (29.87 G tex-1), and highest uniformity index (84.77%), as compared to control treatment (Table 2).

4. DISCUSSION

The availability of nitrogen, which is a vital external nutrient for sustainable crop production, plays a crucial role in maintaining productivity across various cropping systems (Habibullah *et al*., 2018). Lal (2018) highlights the heavy usage of chemical fertilizers, particularly nitrogen fertilizers, in modern Pakistani farming practices, and this trend is expected to continue due to increasing food demand (USDA, 2019). Consequently, there is a need to develop solutions that improve NUE to ensure sustainable cotton production (Iqbal et al., 2016). In the current cropping systems of Pakistan, low NUE can be attributed to several factors, but excessive nitrogen application and the choice of nitrogen sources are the primary contributors. In light of this, the present study aimed to evaluate the effects on cotton production in a field trial by utilizing a commercially available value-added fertilizer known as ZKZ Plus, in combination with standard fertilizers and nitrogen inputs (100% ZKZ Plus + Zingro + Zoron + 100% Standard Urea). Nitrogen is an essential nutrient due to its crucial role in chlorophyll synthesis, photosynthesis, and the conversion of carbon dioxide and water into sugars. It is also a fundamental

component of amino acids, the building blocks of proteins. Effective N management is vital for the healthy growth, productivity, and quality of cotton, as it is the most extensively utilized nutrient among all other essential plant nutrients. In response to the increasing demand for nitrogen fertilizers, researchers are striving to enhance cotton's ability to efficiently utilize nitrogen. Several studies have demonstrated that efficient nitrogen management can improve nitrogen use efficiency, reduce farmer expenses, and enhance farm profitability (Khan *et al*., 2019).

4.1. Effect of commercial value-added fertilizer on crop yield

During cotton development, nitrogen is the most critical limiting nutrient. As nitrogen fertilizer prices continue to rise, proper nitrogen management becomes crucial to increase nitrogen use efficiency and achieve higher-quality yields. Prior to application, soil analysis for nitrogen should be conducted to ensure that fertilizers are applied at the right time, in the appropriate manner, and in the correct amounts, with special attention given to selecting the right nitrogen source (Khan *et al*., 2019). Value-added fertilizers offer an environmentally friendly alternative to conventional chemical fertilizers and can enhance crop output while reducing fertilizer usage (Liu *et al*., 2020). These value-added fertilizers are used across various crops to improve productivity, contrasting with conventional commercial fertilizers. Compared to conventional fertilizer sources, the use of value-added fertilizers can increase crop yields by 14 to 17%. Farmers express satisfaction with these novel value-added fertilizers, as they are easier to handle in the field and have the potential to improve nitrogen use efficiency (Zhao *et al*., 2020).

4.2. ZKZ plus's impact on crop production

According to the study results, the application of N through ZKZ Plus led to increased plant height, a greater number of buds, a higher abundance of closed and open bolls in flowers, greater root biomass, and ultimately a higher seed yield in cotton plants. These findings suggest that ZKZ Plus may have extended the availability of nutrients over a prolonged duration compared to standard urea fertilizers (Keerio *et al*., 2022).

4.3. Effect of ZKZ plus on NUE in cotton

The ZKZ Plus fertilizer, with its composition of NPK 8:23:18, is suitable for a wide range of major crops. The exceptional quality of ZKZ Plus, combined with the appropriate ratio of nitrogen, phosphorus, and potassium (NPK) in each granule, makes it convenient for growers to apply. In contrast to conventional fertilizers, ZKZ Plus incorporates organic fillers, bio-stimulants, and soil conditioners, which contribute to a 10-12% increase in NUE and yield. Furthermore, this value-added fertilizer improves soil health and facilitates the release of crucial minerals that are otherwise inaccessible (Engro, 2019). In comparison to common fertilizers, the findings of the study revealed that the application of ZKZ Plus, a commercially available value-added fertilizer, resulted in notable enhancements in plant height, the number of buds, flowers, and bolls, as well as root biomass and seed cotton production (Keerio *et al*., 2022).

4.4. Influence of value added fertilizer on quality of cotton

In comparison to straight fertilizers, the application of ZKZ Plus resulted in improved NUE, making it a more environmentally friendly fertilizer that reduces nitrogen losses. When compared to conventional fertilizers, ZKZ Plus exhibited significant enhancements in cotton fiber quality. This was evident through improved staple length, micronaire value, fiber strength, and uniformity index (%), all of which play a crucial role in determining cotton fiber quality. However, limited research has been

conducted to explore the effects of the commercial value-added fertilizer, ZKZ Plus, on fiber quality. The ZKZ Plus has been shown to enhance cotton fiber quality through different mechanisms. Firstly, the balanced nutrient formulation in ZKZ Plus support optimal plant nutrition, leading to increase fiber elongation and strength (Karami *et al*., 2017). Secondly, the presence of micronutrients fertilizer such as zinc (Zingro) and boron (Zoron) with ZKZ Plus has been linked to improved fiber fineness and uniformity (Mengel *et al*., 2001). At a national level, the application of ZKZ Plus and similar value-added fertilizers can have significant environmental as well as economic benefits. For instance, a 10% improvement in cotton fiber quality can result in a 5-7% increase in textile exports, generating foreign revenue for the national economy (Pakistan Cotton Ginners Association, 2020).

The findings of this study indicated that increasing the amount of nitrogen through coated urea enhanced nitrogen availability. In comparison to standard fertilizers, applying at least 75% of the total nitrogen as coated urea significantly reduced nitrogen leaching and improved nitrogen agronomic efficiency, while maintaining comparable crop production (Incrocci *et al*., 2020). Nitrogen is one of the most commonly applied nutrients globally through fertilizers, with potassium and phosphorus being used in relatively smaller amounts. Over the past decade, the cost of natural gas, which directly affects the price of nitrogen fertilizers, has experienced a significant increase. Despite the rising cost, farmers sometimes apply excessive amounts of fertilizer, leading to inefficiencies. This widespread reliance on synthetic nitrogen fertilizers has become a major concern for farmers, as it not only drives up costs unnecessarily but also contributes to environmental contamination (Ahmed *et al*., 2016). In terms of cost-benefit analysis, the advantages of ZKZ Plus were found much greater than those of straight fertilizers in this study, resulting in reduced fertilizer costs while achieving required agronomic benefits.

5. CONCLUSION

In conclusion, the findings of this study demonstrate that the application of the commercial value-added fertilizer, ZKZ Plus, resulted in improved NUE by reducing nitrogen losses. Furthermore, ZKZ Plus exhibited significant positive effects on various aspects of cotton crop production. It led to increased plant height, a greater number of buds, flowers, and bolls, as well as enhanced root biomass and seed cotton yield. Additionally, ZKZ Plus improved the quality of cotton fiber, as indicated by improved staple length, micronaire value, fiber strength, and uniformity index (%), surpassing the performance of conventional fertilizers. The research also highlighted the potential of ZKZ Plus to enhance nitrogen availability when applied as coated urea, leading to reduced nitrogen leaching and improved nitrogen agronomic efficiency. These findings are particularly relevant in the context of the widespread use of synthetic nitrogen fertilizers and the associated challenges of excessive fertilizer application and environmental contamination. Moreover, the cost-benefit analysis indicated that ZKZ Plus offered significant advantages over straight fertilizers, resulting in reduced fertilizer costs. Overall, the study endorse the potential of ZKZ Plus as a valuable commercial value-added fertilizer, promoting sustainable cotton production and improved fiber quality.

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