

**Evaluating the fertilizer value of shed cotton fruiting structures under changing environmental conditions**

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ABSTRACT

Review Process: Peer review

Climate change induced environmental stresses have increased the shedding of fruiting structures in cotton altering the return of reproductive biomass/fruitlet structures to the soil. Although these shed fruiting structures contain various plant nutrients in different concentration that may contribute to nutrient cycling. However, their fertilizer value has not been quantified, and current fertilizer recommendations do not account for this potential nutrient contribution. The objective of this study was to quantify the fertilizer value of shed cotton fruiting structures and assess their contribution to nutrient availability, crop productivity, and fertilizer optimization under changing environmental conditions. Field experiments were conducted at three locations (Sakrand, Tandojam, and Ghotki) using a factorial arrangement of fruiting structure management (retained vs. removed) and six fertilizer levels (0, 20%, 40%, 60%, 80%, and 100% of the recommended fertilizer dose, RDF). Yield, yield components, chlorophyll content, quality traits, and nutrient concentrations were evaluated. The three-way interaction among location, fruiting structure management, and fertilizer level was non-significant; however, the individual effects of fertilizer level and fruiting structure management were significant across locations. Seed cotton yield, yield components, and chlorophyll content increased significantly with increasing fertilizer rates, irrespective of fruiting structure treatment. The greatest yields were recorded at 100% RDF, followed by 80%, 60%, 40%, and 20% RDF, all of which exceeded the unfertilized control. The greatest response occurred at location Sakrand, followed by Ghotki and Tandojam locations. Most of the fiber quality parameters were significantly influenced by fertilizer level, irrespective of location and fruiting structure treatments. The quantity of shed fruiting structures was highest at Ghotki, followed by Sakrand and Tandojam locations. Nutrient concentrations (N, P & K) varied significantly across fertilizer levels under the changing environmental conditions. Overall, the results indicated that shed fruiting structures contributed up to 9% of cotton yield through nutrient recycling. These findings demonstrate that cotton fruiting structure shedding represents a measurable amount of plant nutrients and should be considered in future fertilizer planning to improve nutrient availability and climate resilience in cotton growing regions of Sindh, Pakistan.

Keywords: Cotton, changing environment, fertilizer management, shedding, fruiting structures.

INTRODUCTION: Cotton (*Gossypium* spp.), one of Pakistan's major cash crops and commonly known as "white gold" is increasingly threatened by climate change, which has emerged as a critical driver of declining productivity and production system instability. Rising temperatures, erratic rainfall patterns, and the increasing frequency of extreme weather events have adversely affected cotton growth, yield formation, and pest dynamics, compounding existing production constraints (Khan, 2024). Observed evidence further indicates that climate induced stresses particularly temperature stress, droughts, floods, and unpredictable precipitation are significantly disrupting cotton production especially in major cotton growing regions, thereby undermining the sustainability of cotton crop (Khan and Khan, 2025). The global mean near-surface temperature reaching approximately 1.55±0.13°C above the 1850 - 1900 pre-industrial average in 2023. Concurrently, atmospheric CO₂ concentrations reached 423.9±0.2ppm in 2024, compared with approximately 280 ppm during the pre-industrial period, increasing climatic pressure on agricultural ecosystems and crop production (World Meteorological Organization, 2025a; World Meteorological Organization, 2025b). In cotton, elevated temperatures and moisture stress are strongly associated with impaired phenology (Han *et al.*, 2023), reduced water use efficiency, inferior fiber quality, and most critically, excessive shedding of fruiting structures (Cotton Research Development Center, 2020; Rashid *et al.*, 2020). In Pakistan, temperature increases and altered rainfall regimes have already resulted in substantial reductions in cotton yield and its quality (Siyal *et al.*, 2021).

Adequate plant nutrition plays a significant role in maintaining cotton growth, productivity, and fiber quality (Ashraf *et al.*, 2017) under both optimal and stressed conditions, as cotton's physiological and developmental processes are highly sensitive to nutrient supply (Rochester *et al.*, 2012; Constable and Bange, 2015). Deficiencies in nutrients, particularly nitrogen (N), potassium (K), and boron (B) resulted in chlorosis, stunted growth, malformations, and reduced yield and fiber characteristics (Oosterhuis, 2013; Oosterhuis, 2019) because these nutrients regulate photosynthesis, enzymatic activities and reproductive organ development (Oosterhuis, 2019; Zhao, and Oosterhuis,

2001). These deficiencies frequently arise from soil constraints such as low organic matter, poor nutrient supply, high soil pH etc., suboptimal fertilizer management, and environmental stresses that limit nutrient availability and uptake (Qamar *et al.*, 2023; Ahmad *et al.*, 2024).

Cotton is widely cultivated on alkaline calcareous soils, where deficiencies of N, P, and K are especially prevalent and fertilizer use efficiency remains low (Waqas *et al.*, 2023). Consequently, the development of integrated, climate resilient, and nutrient efficient fertilization strategies has become essential for sustaining cotton productivity (Xiao and Yin, 2019). The extent of reproductive shedding in cotton, including squares, flowers, and immature bolls, commonly ranges from 65 to 70%, with considerable variation arising from genotype and prevailing environmental conditions (Baloch *et al.*, 2000; Haneef *et al.*, 2001). Although cotton plants initiate a large number of fruiting sites during the growing season, only about 25–30% ultimately develop into harvestable bolls because many reproductive organs are naturally lost before maturity (Chen *et al.*, 2014). Environmental stresses associated with climate change, particularly elevated temperature and water deficit, further increase the rate of reproductive abscission, leading not only to reduced lint yield but also to greater deposition of reproductive biomass on the soil surface (Bista *et al.*, 2025). While the detrimental effects of fruit shedding on yield have been widely documented, the contribution of this biomass to nutrient cycling within cotton production systems has received comparatively little attention.

The decomposition of plant residues represents one of the primary mechanisms through which nutrients are recycled in agricultural ecosystems. As plant litter decomposes, nutrients contained in plant tissues are gradually mineralized and released into the soil, where they become available for subsequent crop uptake (Rogers, 2002; Demessie *et al.*, 2012). This natural recycling process contributes to the maintenance of soil fertility, stimulates microbial activity, and supports the long-term sustainability of cropping systems (Lindsay and French, 2005; Sayer and Tanner, 2010). In many terrestrial ecosystems, plant litter serves as a temporary nutrient reservoir, returning a substantial proportion of absorbed mineral nutrients through decomposition (Gautam and Mandal,

2018; De la Cruz, 2020). Previous studies conducted in forest and plantation ecosystems have estimated that litterfall may account for 60–80% of annual nutrient recycling, depending on vegetation type, litter quality, and climatic conditions (Berthelot *et al.*, 2000; Salehi *et al.*, 2013). Cotton fields accumulate shed squares, flowers, and immature bolls that differ from leaf litter in nutrient content and decomposition, potentially contributing substantially to nutrient recycling. Recent investigations have shown that reproductive litter decomposes relatively rapidly under field conditions and can return appreciable amounts of N, P, and K to the soil, thereby contributing to internal nutrient cycling and improving nutrient availability for subsequent crop growth (Keerio *et al.*, 2026). Furthermore, studies have demonstrated that improved nutrient management enhances nitrogen use efficiency and fiber quality in cotton, indicating that naturally recycled nutrients should also be considered when developing fertilizer recommendations (Mastoi *et al.*, 2025). The quantity of nutrients released from shed fruiting structures depends on the amount of biomass produced, its chemical composition, and environmental factors that regulate decomposition and mineralization processes (Austin *et al.*, 2009). Nevertheless, existing fertilizer recommendations for cotton largely ignore the nutrient contribution of reproductive litter to be shed fruiting structures of cotton, potentially resulting in overestimation of fertilizer requirements and reduced nutrient use efficiency under changing climatic conditions.

OBJECTIVES: Therefore, the present study aimed to evaluate the fertilizer value of shed cotton fruiting structures and quantify their contribution to nutrient availability, crop productivity, and fertilizer optimization across contrasting environments. It was hypothesized that the inclusion of shed fruiting structures in the litter pool significantly enhances nutrient return and contributes approximately 10 to 20% of decomposition derived nutrients compared with leaf litter alone. This contribution is expected to become more pronounced under variable environmental conditions due to differences in tissue chemistry, decomposition behavior, and nutrient release patterns. This study addresses a key knowledge gap in order to guide climate resilient fertilizer management in sustainable cotton production.

MATERIALS AND METHOD: Study sites and weather data: The study was conducted at three distinct locations across Sindh, Pakistan, under changing environments suitable for cotton cultivation (figure 1). The first site was the Experimental Farm of the Cotton Research Station (CRS) Ghotki, District Ghotki (28°01'10.1"N, 69°19'02.7"E), situated in northern Sindh.

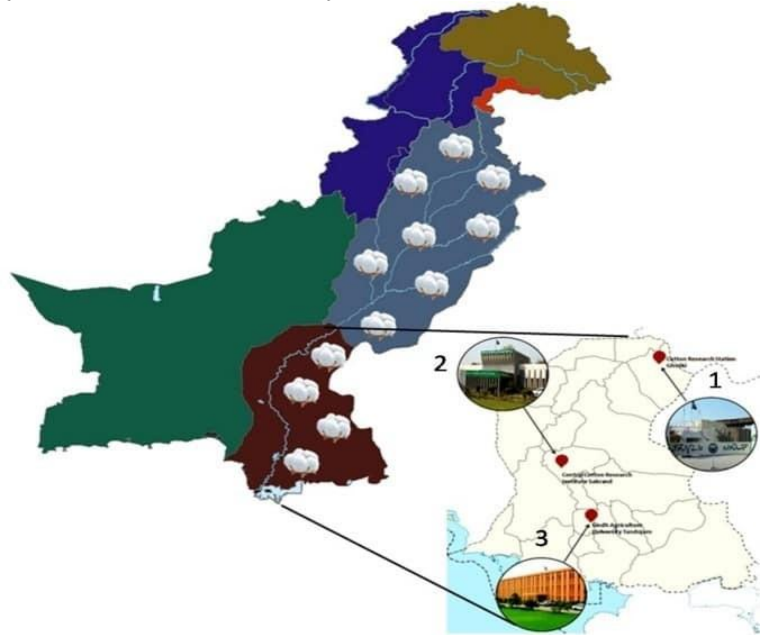


Figure 1: Study sites weather data of selected locations. The second site was the Experimental Farm of the Central Cotton Research Institute (CCRI) Sakrand, District Shaheed Benazirabad (26°08'01.5"N, 68°16'48.1"E), located in the central cotton belt of Sindh. The third site was the Latif Experimental Farm at Sindh Agriculture University, Tandojam, District Hyderabad (25°26'29.1"N, 68°33'36.2"E), positioned in southern Sindh. The weather data (figure 2) from the selected locations indicated that the overall average monthly maximum temperature reached 46°C in Ghotki, followed by Sakrand at 45°C and Tandojam at 43°C

during the crop cycles of both years (2020 and 2021). The average monthly minimum temperature was recorded at 27°C in Tandojam, with Sakrand and Ghotki both at 28°C. The highest average maximum temperature of 46 °C was noted in Ghotki during June 2020. Conversely, the average minimum temperature of 27 °C was observed in Tandojam in August 2021. Throughout both cropping seasons (2020 and 2021), the highest average monthly rainfall was recorded in Tandojam at 77.8 mm, followed by Sakrand at 71.8 mm and Ghotki at 24.2 mm. The peak average monthly rainfalls of 77.8 mm and 41.9 mm were recorded at the Tandojam site in August 2020 and July 2021, respectively. The maximum average humidity was 63% at Tandojam, with Sakrand at 55% and Ghotki at 44%. The highest average monthly humidity of 63% and 58% was recorded at Tandojam during August 2020 and July 2021, respectively. In contrast, the lowest average monthly humidity of 15% was noted at Ghotki in May 2020 and April 2021, respectively (worldweatheronline.com).

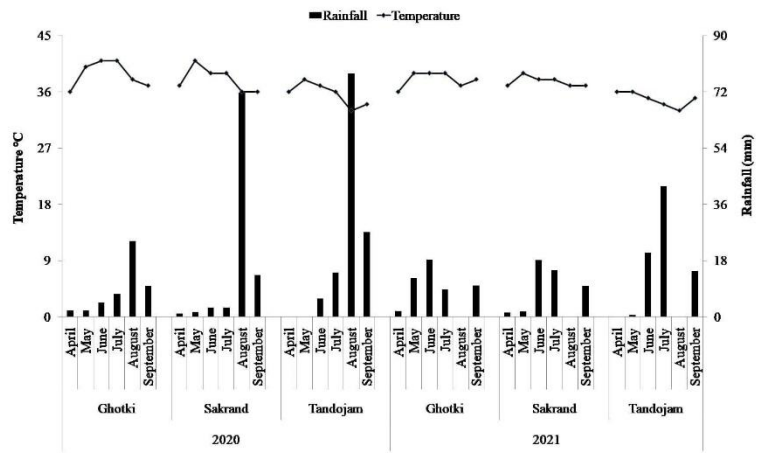


Figure 2: Average monthly temperature (°C) and rainfall (mm) of three locations during the 2020 and 2021

Experimental design: The field experiments were carried out using a Factorial Randomized Complete Block Design (RCBD), with three replications at each locations. The experimental setup included three primary factors. Factor A consisted of three locations that represented various agro-climatic conditions: Sakrand, Tandojam, and Ghotki. Factor B included two levels of fruiting structure management: (+) Fruiting Structures, where the fruiting structures were shed in the field, and (-) Fruiting Structures, where the fruiting structures were collected in cotton shed material collection (CSMC) traps. Factor C comprised six fertilizer treatments, which were: T₁ (Control, no fertilizer), T₂ (100% Recommended Dose of Fertilizer, RDF), T₃ (80% RDF), T₄ (60% RDF), T₅ (40% RDF), and T₆ (20% RDF). For this research, the cotton variety CRIS-129 was selected as the test crop. This particular cultivar was intentionally selected due to its sensitivity to the shedding of fruiting structures (Central Cotton Research Institute Sakrand, 2018), enabling a more accurate assessment of the treatment effects on fruit retention and shedding under various nutrient and management conditions across different environments. The experiment was conducted over a total area of 2100 ft², which was divided into 18 sub-plots. A total of 40 plants were sown per treatment, with 10 plants maintained for recording the observations.

Soil analysis: Composite soil samples were collected from depths of 0-15 cm and 15-30 cm before the sowing at all experimental sites, including Ghotki, Sakrand, and Tandojam. These soil samples were brought to the Soil Science Department laboratory at Sindh Agriculture University, Tandojam. The samples were air-dried, ground, passed through a 2 mm sieve, and subsequently packed in plastic bottles for further analysis. Following processing, the soil samples analyzed for various physico-chemical properties, which included soil texture assessed by the hydrometer method, electrical conductivity and pH measured using a pH & Conductivity Meter (Jenway-3540, Barloworld Scientific Ltd., Dunmow, Essex, UK), organic matter determined by the Walkley-Black method, total nitrogen analyzed via the Kjeldahl method, and extractable phosphorus and potassium analyzed through the AB-DTPA method (Ryan *et al.*, 2001).

Preparation and installation of cotton shed material collection trap: Cotton shedding material collection (CSMC) trap were prepared from cloth for the collection of shed fruiting structures (Leaves, square, flower, bolls). The size each CSMC trap

was 0.5m x 1m x 1m (0.5 m³) in size and installed on surface under the canopy of three selected plants of each treatment (figure 3). The traps were installed after 30 days of germination of the crop with the help of 3 to 4 wooden sticks of 1 meter height. The CSMC traps were unfolded in upward direction to adjust at height of the plants. The shed fruiting structures were collected from each CSMC trap on monthly basis and brought into the laboratory to separate into the, leaves, squares, and flowers. Dry weight of each shed material was taken.

Growth traits and seed cotton yield: At the time of crop maturity (150 days after planting), ten plants were selected and tagged from each treatment to record various growth and yield parameters. These parameters included plant height (cm), number of sympodial branches per plant, number of fruiting points per plant, number of bolls per plant, boll weight (g), 100 seed weight (g), seed cotton yield per plant and seed cotton yield (kg ha⁻¹). Furthermore, the SPAD value was recorded using the Minolta SPAD-502 Chlorophyll Meter during the second week of blooming by averaging the twenty SPAD readings of fifth fully expanded leaves below the terminal of each plant (Johnson and Saunders, 2003).



Figure 3: Cotton shedding material collection (CSMC) trap.

Cotton fiber quality: Twenty-five bolls from each treatment were hand picked and brought to the laboratory for assessment of fiber quality parameters. The lint and seed were separated using a ginning machine (single plant saw ginner-6204). A sample of thirty grams of lint, free from foreign matters was used to determine the fiber quality parameters. The quality parameters, which included staple length (mm), fiber strength (g tex⁻¹), micronaire value (ug inch⁻¹) and uniformity index (%) were measured using a high volume instrument (HVI-900A) system.

Plant analysis: The fifth fully expanded leaf from the terminal at the full bloom stage was selected as the sampling unit. From each treatment group, twenty-five leaves were randomly collected to ensure a representative sample. The collected leaves were promptly placed in clean, appropriately labeled polyethylene bags to avoid contamination or mixing of samples, and subsequently brought to the laboratory for further processing. In the laboratory, the samples were initially prepared and analyzed for their nutrient content. The total N concentration was determined using the Kjeldahl digestion method, P and K concentrations through wet digestion using nitric acid and perchloric acid (2:1) using spectrophotometer (U-2900 Hitachi) and flame photometer Corning-400 (Ryan *et al.*, 2001).

Fertilizer contribution (%): The role of fertilizer in yield enhancement was assessed through a comparative method that analyzed the difference in seed cotton yield between treatments with (+) Fruiting Structures, where the fruiting structures were shed in the field, and (-) Fruiting Structures, where the fruiting structures were collected in cotton shed material collection (CSMC) traps. The fertilizer contribution percentage was calculated using the following formula developed in this study:

$$\text{Fertilizer Contribution (\%)} = \frac{\text{Yield obtained under (+) fruiting structures} - \text{Yield obtained under (-) fruiting structures}}{\text{Yield obtained under (-) fruiting structures}} \times 100$$

In this formula, the yield measured from treatments with (+) fruiting structures reflect the potential yield achieved when fruiting structures are permitted to remain on the plant, whereas the yield from (-) fruiting structures act as the reference point. The difference between these two figures, represented as a percentage of the yield from (-) fruiting structures, signifies the relative impact of fertilizer application on the total crop yield.

Statistical analysis: The data were subjected to factorial analysis of variance (ANOVA) according to the experimental design described using Statistix 9.1 software (Analytical software, Tallahassee, FL, USA). The significance of treatment effects and

their interactions was tested using the F-test. When ANOVA indicated significant differences among treatment means, mean separation was performed using the least significant difference (LSD) test at 5% probability level ($P \leq 0.05$).

RESULTS: Physico-chemical properties of soils of experimental sites:

The analytical findings regarding the physio-chemical properties of the soils from the experimental sites before the planting during the years 2020 and 2021 indicated that the soils in Ghotki had a sandy clay loam texture, while those at both the Sakrand and Tandojam sites exhibited a loam texture. The soils in Ghotki and Tandojam were classified as non-saline, in contrast to the slightly saline soils found at the Sakrand site. Additionally, the soils across all sites demonstrated an alkaline reaction. In terms of nutrient content, all sites were found to be deficient in nitrogen (N) and phosphorus (P), while being adequate in extractable potassium (K) and low in organic matter content (table 1).

Agronomic parameters: Results regarding the plant height (cm), number fruiting points plant⁻¹, and number bolls plant⁻¹ presented in Figure 4, 5 and 6, indicated that the plant height (cm) responded significantly ($P < 0.05$) to different fertilizer levels and location x fruiting status under changing environmental conditions during both year. Overall plant height ranged from 111.7 cm to 160.3 cm in 2020 and 107.4 cm to 155.0 cm in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. Maximum plant height was observed in Sakrand followed by Tandojam and Ghotki during both the years. Number of fruiting point plant⁻¹ affected significantly ($P < 0.05$) to different fertilizer levels and fertilizer levels x location under changing environmental conditions during the 2020 and 2021. Overall number of fruiting points plant⁻¹ varied from 25.5 to 51.5 in 2020 and 22.1 to 48.7 in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. Maximum number of fruiting point plant⁻¹ was observed in Sakrand followed by Tandojam and Ghotki during both the years. Number of bolls plant⁻¹ positively and significantly ($P < 0.05$) affected to different fertilizer levels under changing environment during the 2020 and 2021. Overall number of bolls plant⁻¹ varied from 17.8 to 41.1 in 2020 and 15.2 to 40.0 in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. Highest number of bolls plant⁻¹ was noted in Sakrand followed by Tandojam and Ghotki during both the years. Boll weight (g) significantly ($P < 0.05$) affected to different fertilizer levels under changing environmental conditions during the 2020 and 2021.

Chlorophyll content (%): Chlorophyll content (%) positively and significantly ($P < 0.05$) affected to different fertilizer levels and location x fruiting status under changing environment during the 2020 and 2021 (figure 7). Overall chlorophyll content ranged from 46.9 % to 70.2 % in 2020 and 48.5 % to 71.8 % in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. The greatest chlorophyll content was recorded in Tandojam followed by Sakrand and Ghotki during both the years.

Seed cotton yield (kg ha⁻¹): Seed cotton yield (kg ha⁻¹) positively and significantly ($P < 0.05$) affected to different fertilizer levels, fertilizer levels x location, fertilizer level x fruiting status, and location x fertilizer level x fruiting status under changing environment during the 2020 and 2021 (figure 8). Overall Seed cotton yield ranged from 769 kg ha⁻¹ to 2118 kg ha⁻¹ in 2020 and 939 kg ha⁻¹ to 2511 kg ha⁻¹ in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. The highest Seed cotton yield was recorded in Sakrand followed by Tandojam and Ghotki during both the years.

Shedding of fruiting structures (squares, flowers) and leaves:

Shedding of fruiting structures on monthly basis affected significantly ($P < 0.05$) with the different fertilizer levels under changing environment more in 2020 than 2021 (figure 9). Quantity wise leaves shed more followed by flowers and squares. Location-wise more shedding of fruiting structures were observed in Ghotki followed by Sakrand and Tandojam during both the consequent years. The highest quantity (1837 kgha⁻¹) leaves shedded at Ghotki, (587 k gha⁻¹) flowers and (442 kgha⁻¹) squares at Sakrand were shedded. While, the minimum shedding of leaves (959 kg ha⁻¹), squares (191 kg ha⁻¹) and flowers (186 k gha⁻¹) were observed in Tandojam. Overall total quantity of fruiting structures shed was 2857 kg ha⁻¹ in Sakrand, 2535 kg ha⁻¹ in Ghotki and 1669 kg ha⁻¹ in Tandojam during 2020. While during the 2021 in Ghotki 2240 kg ha⁻¹, in Sakrand 2177 kg ha⁻¹ and in Tandojam 1380 kg ha⁻¹ were

shedded and contributed as fertilizer by the cotton plants. The observed shedding of leaves, flowers and squares represented not only a natural component of cotton growth and development but also a potential sources of organic material and nutrients that can contribute to maintaining soil fertility under changing environmental conditions.

Properties	CRS-Ghotki		CCRI-Sakrand		SAU Tandojam	
	2020	2021	2020	2021	2020	2021
Textural class	Sandy Clay Loam	Sandy Clay Loam	Loam	Loam	Loam	Loam
Electrical Conductivity (dSm ⁻¹)	2.73	3.65	5.00	4.80	2.00	2.40
pH (1:1)	8.70	8.80	8.40	8.60	8.20	8.00
Organic Matter (%)	0.64	0.60	0.62	0.68	0.72	0.67
Nitrogen (%)	0.032	0.030	0.031	0.034	0.036	0.034
AB-DTPA Phosphorus (mgkg ⁻¹)	2.00	3.10	10.10	9.80	6.80	7.20
AB-DTPA Potassium (mgkg ⁻¹)	180.00	196.00	324.00	344.00	198.00	185.00

Table 1: Physico-chemical properties of soils of selected experimental sites.

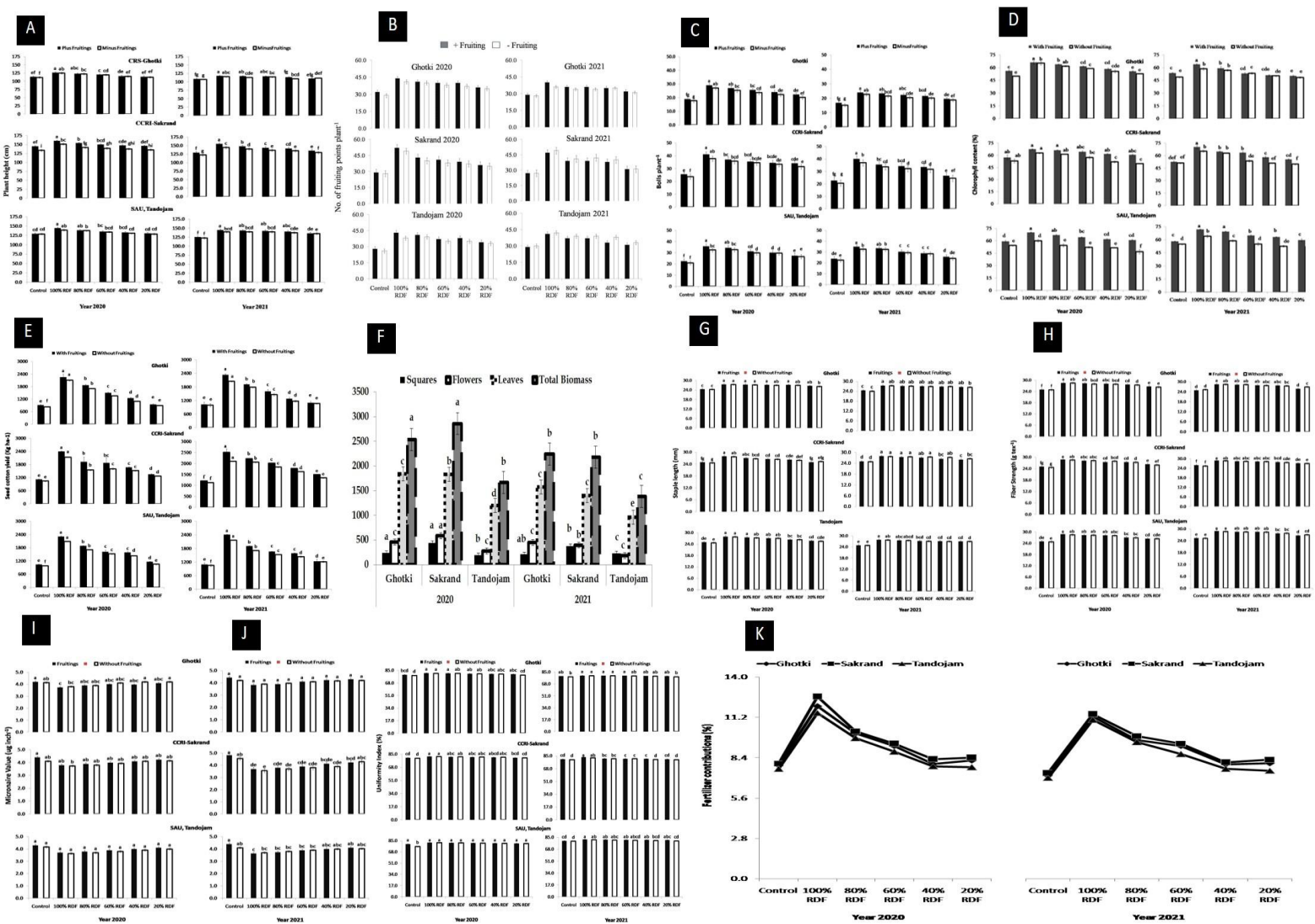


Figure 4: Plant height (A), number of fruiting point per plant (B), bolls per plant (C), chlorophyll content (D), seed cotton yield (E), total shedding of fruiting structure and leaves (F), staple length (G), fiber strength (H), micronaire value (I),uniformity index (J) and fertilizer contribution (K) under changing environment during 2020 and 2021.

Staple length (mm): Staple length (mm) significantly ($P<0.05$) affected to different fertilizer levels, fertilizer level x location, fertilizer level x fruiting status,, location x fruiting status, and location x fertilizer level x fruiting status under changing environment during the 2020 and 2021 (figure 10). Overall staple length ranged from 24.4 mm to 28.0 mm in 2020 and 24.1 mm to 28.0 mm in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. The maximum staple length was recorded in Sakrand followed by Tandojam and Ghotki during both the years.

Fiber strength (g tex⁻¹): Fiber Strength (g tex⁻¹) significantly ($P<0.05$) affected to different fertilizer levels, fertilizer level x location, fertilizer level x fruiting status, and location x fertilizer level x fruiting status under changing environment during the 2020 and 2021 (figure 11). Fiber strength (gtex⁻¹) ranged from 24.7g tex⁻¹ to 28.9 g tex⁻¹in 2020 and 24.9g tex⁻¹to 29.0g tex⁻¹in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. The maximum fiberstrength (gtex⁻¹) was recorded in Sakrand followed by Tandojam and Ghotki during both the years.

Micronaire value (ug inch⁻¹): Micronaire Value (ug inch⁻¹) significantly ($P<0.05$) affected to different fertilizer levels under changing environment during the 2020 and 2021 (figure 12). Overall micronaire value ranged from 3.63ug inch⁻¹to 4.2ug inch⁻¹in 2020 and 3.6 ug inch⁻¹to 4.8ug inch⁻¹in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam. The

maximum micronaire value was recorded in Sakrand followed by Tandojam and Ghotki during both the years.

Uniformity index (%): Uniformity index (%) significantly ($P<0.05$) affected to different fertilizer levels, fertilizer level x location, and location x fertilizer level x fruiting status under changing environment during the 2020 and 2021 (figure 13). Overall uniformity index ranged from 76.3% to 82.2%in 2020 and 78.2% to 82.3% in 2021 in plus fruiting and minus fruiting structures at Ghotki, Sakrand and Tandojam.The maximum uniformity index was recorded in Sakrand followed by Tandojam and Ghotki during both the years.

Nitrogen, phosphorus and potassium concentration (%) in cotton leaves: The N, P and Kconcentration (%) significantly ($P<0.05$) affected to different fertilizer levels under changing environment during the 2020 and 2021 (Table 2). In cotton leaves at the late bloom maturity N ranged from 2.10% to 4.20%, P ranged from 0.04 % to 0.20% and K ranged from 0.76% to 1.67% under changing environment. Maximum N%, P% and K% was recorded from the Ghotki followed by Sakrand and Tandojam during the year 2020 than the year 2021 in plus and minus fruiting structures. Further, N, P and K percents in cotton leaves were decreased as the fertilizer dose was decreased and the maximum percents were noted where the recommended dose of fertilizer was applied.

Location	Nutrients	2020						2021					
		Control	100% RDF	80% RDF	60% RDF	40% RDF	20% RDF	Control	100% RDF	80% RDF	60% RDF	40% RDF	20% RDF
Ghotki	N Concentration (%)												
	With Fruiting	2.60 d	4.2 0a	4.00 a	3.50b	3.40 b	3.10 c	2.50 d	4.00 a	3.90 a	3.40 b	3.30 bc	3.00 c
	Without Fruiting	2.50 d	4.00 a	3.90 a	3.50 b	3.30 b	3.00 c	2.40 d	3.90 a	3.80 a	3.30 b	3.10 bc	3.10 c
	P Concentration (%)												
	With Fruiting	0.09 e	0.20 a	0.19 ab	0.17 bc	0.15 cd	0.13 d	0.07 d	0.19 a	0.18 ab	0.16 b	0.16 b	0.12 c
	Without Fruiting	0.07 e	0.19 a	0.18 ab	0.15 bc	0.14 c	0.11 d	0.05 d	0.18 a	0.17 ab	0.15 b	0.15 b	0.10 c
	K Concentration (%)												
	With Fruiting	0.80 e	1.67 a	1.62 ab	1.56 bc	1.51 c	1.40 d	0.78 e	1.66 a	1.59 b	1.57 bc	1.51 c	1.40 d
Sakrand	Without Fruiting	0.76 d	1.64 a	1.61 a	1.54 b	1.49 b	1.38 c	0.76 e	1.63 a	1.56 b	1.55 b	1.49 c	1.39 d
	N Concentration (%)												
	With Fruiting	2.37 d	4.10 a	4.00 a	3.57 b	3.23 c	2.97 c	2.57 d	4.00 a	3.83 a	3.50 b	3.10 c	2.90 c
	Without Fruiting	2.17 d	4.03 a	4.00 a	3.37 b	3.10 c	2.93 c	2.37 d	3.97 a	3.73 a	3.30 b	2.90 c	2.73 c
	P Concentration (%)												
	With Fruiting	0.08 e	0.19 a	0.17 b	0.16 bc	0.14 cd	0.12 d	0.06 d	0.18 a	0.18 a	0.15 b	0.14 bc	0.12 c
	Without Fruiting	0.05 d	0.18 a	0.16 b	0.14 b	0.12 c	0.10 c	0.04 d	0.17 a	0.17 a	0.14 b	0.13 b	0.10 c
	K Concentration (%)												
Tandojam	With Fruiting	0.77 d	1.65 a	1.59 a	1.56 ab	1.48 bc	1.39 c	0.77 d	1.64 a	1.57 ab	1.54 ab	1.47 bc	1.37 c
	Without Fruiting	0.74 e	1.63 a	1.57 b	1.56 bc	1.47 c	1.36 d	0.74 e	1.62 a	1.56 ab	1.51 bc	1.45 c	1.35 d
	N Concentration (%)												
	With Fruiting	2.20 d	4.03 a	3.80 b	3.40 b	3.00 c	2.87 c	2.10 e	3.93 a	3.67 b	3.33 c	2.87 d	2.83 d
	Without Fruiting	2.03 e	3.93 a	3.60 b	3.33 c	3.00 d	2.73 d	2.16 d	3.80 a	3.53 a	3.10 b	2.67 c	2.60 c
	P Concentration (%)												
	With Fruiting	0.06 c	0.18 a	0.16 a	0.16 a	0.12 b	0.11 b	0.04 d	0.17 a	0.16 a	0.14 b	0.13 b	0.10 c
	Without Fruiting	0.04 d	0.17 a	0.15 b	0.14 b	0.10 c	0.09 c	0.03 d	0.15 a	0.14 a	0.12 ab	0.11 b	0.07 c
	K Concentration (%)												
	With Fruiting	0.76 d	1.63 a	1.55 ab	1.536 ab	1.46 b	1.36 c	0.76 d	1.62 a	1.52 ab	1.49 ab	1.44 b	1.33 c
	Without Fruiting	0.75 f	1.61 a	1.53 b	1.49 c	1.44 d	1.34 e	0.73 f	1.60 a	1.51 b	1.46 c	1.42 d	1.31 e

Table 2: : Nutrient concentrations in cotton index tissue.

Fertilizer contribution (%) of shed material from cotton under changing environment: Fertilizer contribution of shed fruiting structures from cotton ranged 7% to 12.6% under changing environment during 2020 and 2021 (figure 14). Overall maximum fertilizer contribution observed from Sakrand followed by Ghotki and Tandojam. Maximum fertilizer contribution 12.6% noted from Sakrand at 100% recommended dose during 2020 and minimum 7% from Tandojam in control plot during 2021. It was confirmed the overall fertilizer contribution of shedded fruiting structure of Ghotki, Sakrand and Tandojam for the year 2020 and 2021.

DISCUSSION: Environmental conditions play a critical role in determining cotton productivity by influencing reproductive development, nutrient uptake, and biomass allocation. Elevated temperatures and moisture stress increase the shedding of squares, flowers, and young bolls, resulting in substantial yield losses (Arshad *et al.*, 2021; Khalid *et al.*, 2025). The present study further demonstrated that these shed reproductive structures serve as a valuable source of organic matter and plant nutrients following decomposition, thereby contributing to nutrient recycling within the cotton production system. Despite their potential to improve soil fertility and nutrient-use efficiency, the fertilizer value of shed cotton fruiting structures has received limited attention in nutrient management and fertilizer recommendation strategies (Vieira, 2018; Ramanjaneyulu *et al.*, 2021). Application of increasing fertilizer rates significantly improved plant growth, chlorophyll content, boll production, and seed cotton yield across all experimental locations. Adequate nutrient availability supports leaf expansion, photosynthesis, reproductive growth, and assimilated translocation, resulting in greater boll retention and biomass accumulation. The superior performance obtained with the recommended fertilizer dose confirms that balanced nutrition remains essential for sustaining cotton productivity under changing environmental conditions. Similar improvements in growth and yield following balanced fertilization have been reported by Rochester *et al.* (2012) and Mastoi *et al.* (2025), who concluded that improved nutrient management enhances nitrogen use efficiency, lint production, and fiber quality under field conditions.

The major contribution of this study is the quantification of the fertilizer value of shed cotton fruiting structures. Although reproductive shedding is generally considered a direct cause of yield loss, the returned biomass acts as a reservoir of nutrients that gradually become available through decomposition (Keerio *et al.*, 2026). Depending on fertilizer level and environmental conditions,

retained fruiting structures contributed between 7 and 12.6% to fertilizer value and increased seed cotton yield by approximately 9% through nutrient recycling. These findings indicated that fruiting structures of cotton should be regarded as part of the nutrient management and internal nutrient cycling process rather than simply as crop waste. Similar conclusions regarding nutrient availability through decomposition of cotton fruiting structures have recently been reported by Keerio *et al.* (2026), who showed that the decomposition of reproductive litter releases appreciable amounts of nutrients back into the soil and can improve nutrient availability for subsequent crop growth. Therefore, fertilizer recommendations may be refined by considering nutrients returned from naturally shed reproductive biomass. Marked differences among locations reflected the influence of environmental conditions on both crop performance and reproductive shedding. Ghotki experienced the highest temperatures and consequently exhibited greater shedding of reproductive structures, whereas Sakrand produced the highest yield and fertilizer contribution. Elevated temperature is known to disturb pollen viability, carbohydrate transport, and hormonal regulation, resulting in increased square and boll abscission. At the same time, greater reproductive biomass deposition under warmer conditions may enhance nutrient return following decomposition. These observations agree with previous reports that heat stress increases fruit shedding while simultaneously altering nutrient cycling within the crop ecosystem (Rashid *et al.*, 2020; Arshad *et al.*, 2021).

Leaf concentrations of N, P, and K increased consistently with fertilizer application, indicating improved nutrient uptake under balanced fertilization. The N is directly associated with chlorophyll formation and protein synthesis, P regulates energy transfer and reproductive development, whereas K controls enzyme activation, osmotic adjustment, and assimilate transport. Consequently, plants supplied with the recommended fertilizer dose maintained superior nutritional status throughout the growing season. Similar nutrient uptake responses have been documented by Vieira (2018), who reported that cotton nutrient accumulation closely follows fertilizer availability and yield potential. Furthermore, Zia-ul-Hassan *et al.* (2014) demonstrated that efficient K nutrition improves nutrient utilization, biomass production, and lint yield, particularly under conditions where potassium availability may limit crop performance. The present findings support these observations by showing that balanced fertilization enhanced nutrient accumulation irrespective of location. The higher

chlorophyll content observed under increasing fertilizer levels further confirms the beneficial effect of adequate nutrition on photosynthetic efficiency. Nitrogen forms the structural basis of chlorophyll molecules, while potassium regulates stomatal activity and carbon assimilation. Improved chlorophyll content therefore translated into greater photosynthetic capacity and increased assimilates availability for boll development (Read *et al.*, 2006; Hu *et al.*, 2017). This physiological response likely contributed to the greater yield recorded under higher fertilizer rates and supports the concept that nutrient availability is closely linked with crop productivity under environmental stress. Balanced nutrition also improved fiber quality characteristics, including staple length, fiber strength, micronaire, and uniformity index. Fiber development depends on continuous carbohydrate supply and efficient nutrient transport during boll filling (Read *et al.*, 2026).

Potassium has a particularly important role in cellulose synthesis and fiber elongation, while adequate N supports biomass production without compromising fiber maturity when supplied at optimum levels. The beneficial influence of K on cotton growth and fiber development reported by Zia-ul-Hassan *et al.* (2014). Likewise, Mastoi *et al.* (2025) reported that improved nutrient management enhances both N use efficiency and fiber quality, supporting the improvements observed in this study. Although boron was not evaluated directly in the present experiment, reproductive development and retention are known to depend on adequate boron nutrition because boron is involved in pollen viability, fertilization, carbohydrate movement, and cell wall formation. Boron deficiency frequently results in poor boll retention and reduced fiber quality. The importance of balanced micronutrient nutrition in sustaining reproductive growth has been demonstrated by Shah *et al.* (2015), who reported significant improvements in cotton performance under adequate boron supply. These findings highlight that optimization of fertilizer strategies should consider both macro- and micronutrients to maximize nutrient use efficiency under changing climatic conditions.

Overall, the present investigation demonstrated that climate-induced shedding should not be regarded solely as a negative consequence of environmental stress. Although excessive shedding reduces harvestable yield, the decomposition of shed reproductive biomass returns valuable nutrients and organic matter to the soil, contributing to internal nutrient cycling and partially compensating for nutrient removal by the crop (Ramanjaneyulu *et al.*, 2021; Vieira, 2018). Incorporating this natural nutrient contribution into fertilizer management could improve nutrient-use efficiency, reduce fertilizer inputs and production costs, and promote more sustainable cotton production under changing climatic conditions (Mukhtar, 2022). Future research should quantify nutrient mineralization from different shed reproductive structures across diverse soil types and climatic conditions to develop fertilizer recommendation models that explicitly account for this internal nutrient source (Prescott, 2010; Manzoni *et al.*, 2017).

CONCLUSION: It was concluded from the study that changing environmental conditions induced shedding of cotton fruiting structures constitutes a quantifiable and agronomically significant internal nutrient source under changing environmental conditions. Across three agro-ecological locations, fertilizer application improved growth, yield components, chlorophyll content, and fiber quality; however, the retention of shed fruiting structures consistently enhanced nutrient availability and crop performance compared with their removal. Shed reproductive biomass contributed approximately 7–12.6% to fertilizer value, corresponding to about a 9% increase in seed cotton yield nutrient recycling. This contribution was consistent across locations and fertilizer levels, despite environmental variability, and increased higher temperatures due to greater biomass shedding. These findings indicate that fruiting structure shedding is not solely a yield loss process but also a measurable pathway of nutrient return, which should be considered in fertilizer management to improve nutrient use efficiency and climate resilience in cotton production systems

ACKNOWLEDMENT: The authors gratefully acknowledge the research and field staff of the Cotton Research Station (CRS), Ghotki, the Central Cotton Research Institute (CCRI), Sakrand, and Sindh Agriculture University (SAU), Tandojam, for providing the

facilities and technical support required to conduct this study. The authors also extend their sincere appreciation to their colleagues and laboratory personnel for their valuable assistance with field experimentation, sample processing, laboratory analyses, data collection, and statistical analysis.

CONFLICT OF INTEREST: All the authors declared no conflict of interest.

LIFE SCIENCE REPORTING: In current research article no life science threat was reported

ETHICAL RESPONSIBILITY: This is original research, and it is not submitted in whole or in parts to another journal for publication purpose.

INFORMED CONSENT: The author(s) have reviewed the entire manuscript and approved the final version before submission.

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