Research Article

In-Situ Decomposition Dynamics of Cotton Fruiting Structures Under Changing Environmental Conditions

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Abstract | Cotton (*Gossypium hirsutum* L.) sheds a significant portion of its fruiting structures, however the decomposition of these residues and their contribution to soil nutrient cycling remain poorly understood. This study was conducted during 2020 and 2021 across three cotton growing locations of Sindh, Pakistan, namely Cotton Research Station (CRS)-Ghotki, Central Cotton Research Institute (CCRI)-Sakrand, and Sindh Agriculture University (SAU)-Tandojam to evaluate the decomposition dynamics of cotton fruiting structures (squares, flowers, leaves, and mixtures) under changing climate. Residues were placed in mesh bags, buried at 20 cm soil depth, and monitored two-month intervals to assess mass loss, decomposition constant (k), mean residence time (MRT), and nutrient release (C, N, P, K). Decomposition varied significantly by location and season, with faster mass loss under warm, humid conditions. Leaves and flowers decomposed more rapidly than squares due to their lower C:N ratios, while squares and mixed residues showed slower breakdown and longer MRT. Leaves contained the highest nutrient concentrations, whereas higher C:N ratios in squares and flowers limited nutrient turnover. Temperature and rainfall were positively correlated with decomposition rates, while higher humidity prolonged MRT. These findings revealed that cotton fruiting residues were integral to soil organic matter (OM) formation and nutrient cycling. They further emphasized the need to incorporate their *in-situ* decomposition into soil fertility management strategies to enhance nutrient availability and strengthen system resilience under changing climatic conditions.

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Introduction

Globally, cotton is the most important natural fiber with economic significance; it plays an important role in boosting the agricultural based economic growth of the country. Its yield is contingent upon environmental factors and agricultural management techniques. In recent years, climate change caused yield losses (Abbas and Waheed 2017; Soomro *et al*., 2020). Cotton, often called as "white gold", has long been the leading cash crop in Pakistan's agriculture. Serving as the backbone of the textile industry, it accounts for nearly 60% of the country's total exports. However, over the past decade, cotton production in Pakistan has steadily declines, facing multiple challenges. Output is projected to fall to just 6.9 million bales in the 2024-25 season, compared to 15 million bales a decade earlier. Alarming, this decline comes at one of the most critical times for the sector. Several factors have driven this downturn, including climate change, outdated farming practices and other production constrains (Hussain *et al*., 2025). Worldwide, Pakistan is among the world's leading countries in cotton production, export and consumption (Shuli *et al*., 2018). In the Sindh province, cotton is widely cultivated in the hot and dry regions of Nawabshah, Sanghar, Noshehroferoz and Ghotki districts (Coticticts, 2021). The extended heat stress induces physico-morphological and biochemical changes in cotton (Abbas, 2020), it affects flowering, pollen fertility, and the number of bolls per plant, ultimately reducing the cotton yield potential. Inefficient fertilizer use during critical growth stages not only disrupts various phases of cotton development but also lowers overall yield (Ahmad and Raza, 2014).

The residues of plants are major source of soil organic matter. Consequently, proper management of soil organic matter needs a better understanding to decomposition kinetics of plant residues sequentially to synchronize the release of nutrients during decomposition and plant uptake as well as to prevent nutrient losses (Duong, 2009). Abiotic factors, such as temperature and moisture by affecting soil microbial activity. This activity tends to increase with rising temperatures, particularly within the optimal range of 30 to 45 °C. Furthermore, the relationship between temperature and microbial activity is contingent upon the specific microbial species involved (Berg and McClaugherty, 2003). Plant litter (shedded material) production and their decomposition are the two important processes that provide the primary input of organic matter to soil and regulate nutrient cycling patterns in forest ecosystems (Facelli and Pickett, 1991; Singh *et al*., 1999; Weltzin *et al*., 2005). Decomposition is the primarily biological process in which organic substances decomposed into mineral components and partially transformed into stable humus forms. The amount of plant material is a key factor that succeeds the nutrient cycle's sustainability in agro-ecosystem, particularly in organic farming (Toleikiene *et al*., 2020). The breakdown of cotton residue adds nutrients and organic matter to the soil. Cotton leftovers like stalks and bolls break down quickly in the soil because to the action of soil microorganisms, particularly in warm, humid environments. This procedure aids in the accumulation of organic matter in cotton-growing soils (Hake *et al*., 1991). The breakdown of plant residues in field conditions is influenced by a mix of physical, chemical, and biological processes, specifically leaching, fragmentation, microbial mineralization, and humification, which facilitate nutrient release and the formation of soil organic matter. The characteristics of the residue, especially its lignin and nitrogen content, play a crucial role in determining the rates of decomposition; litter that contains higher levels of lignin tends to decompose at a slower rate (Rowinska *et al*., 2024). While extensive research has been dedicated to the breakdown of basal residues such as stalks and leaves, there is a scarcity of studies that specifically address the *in-situ* decomposition of cotton fruiting structures (e.g., bolls). For example, research on the decomposition of cotton stalks has shown significant mass loss and nutrient release (N, P, K) when these residues were integrated into the soil and monitored over time using litterbag techniques indicating that analogous methods could clarify the fate of fruiting structures (Jing *et al*., 2016).

In cotton crop, shedding and appearance of fruiting structures (squares, flowering and bolls) and leaves are typically occurred during reproductive phase of cotton crop life cycle. Generally, shedding of squares, flowers and bolls is 60, 8 and 5% respectively is common. Shedding of fruiting structures depends on environmental as well as hereditary factors. One estimate indicated that approximately 60% squares and young bolls are being shedded under normal growing conditions (Verbree, 2013). Thus, shedding of fruiting structures can alter the soil nutrients availability consequently affect cotton nutrient management. Therefore, this study aimed to evaluate the decomposition dynamics and nutrient release patterns of cotton fruiting structures under varying environmental conditions in Sindh Province.

Materials and Methods

Study sites information and experimental design

The research study was carried out in three districts of Sindh Province, Pakistan, namely Ghotki, Shaheed Benazirabad (Nawabshah), and Hyderabad, considering changing environment during the years 2020 and 2021. The study sites information where the trials took place are presented in Table 1.

Table 1: *Study site information*

S.No.	District	GPS reading	Location/Institute
1	Ghotki	28°01'10.1"N 69°19'02.7"E	Experimental farm of Cotton Research Station Ghotki
2	Shaheed Benazirabad (Nawabshah)	26°08'01.5"N 68°16'48.1"E	Experimental farm of Central Cotton Research Institute Sakrand
3	Hyderabad	25°26'29.1"N 68°33'36.2"E	Latif Experimental Farm, Sindh Agriculture University Tandojam

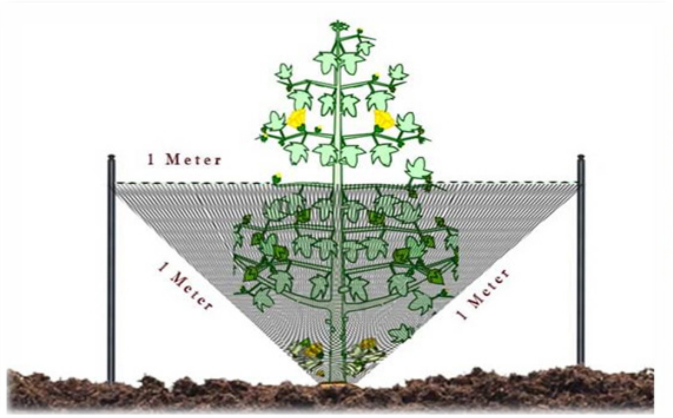

Figure 1: *Schematic diagram of cotton shedding material collection (CSMC) trap*

Collection of cotton fruiting structures

Fruiting structures of cotton, including squares, flowers, leaves, and their combinations, were collected from experimental trials conducted at three distinct locations: CRS-Ghotki, CCRI-Sakrand, and SAU, Tandojam. Cotton shedding material collection (SCMS) trap (Figure 1) measuring 0.5m x 1m x 1m (0.5 m^3) were designed to collect these materials and were positioned on three plants for each treatment. The collected shed material was transported to the laboratory, where the plant materials were categorized into squares, flowers, and leaves, and subsequently prepared for filling mesh bags for decomposition purposes.

Mesh bags placement and sampling strategy

Thirty-six mesh bags with the size of 15x16 cm filled with 10 g of each fruiting structures (square, flower, leaf and mixture of all) with three replications across three sampling intervals (4 fruiting structures x 3 replications x 3 sampling intervals = 36) and were placed at the depth of 20 cm in the cotton field at selected locations (Pandy *et al*., 2017).

Sampling strategy

Four bags, each composed of distinct materials, were taken from every replication at each sampling interval (three sampling intervals of two-month durations) during two growing seasons. Samplings were made during May, July, and September. The residual fruiting structure components were meticulously separated from the bags, rinsed by gently pouring water to eliminate adhering soil particles after brushing the exterior of the mesh bags, and subsequently dried and weighed. The mass loss during drying was calculated for each individual sample. Data related to sampled mesh bags at each interval of sampling were collected to produce an average for the plot. The decomposition rate constant (k) for each sample at every sampling interval was determined utilizing the exponential model derived from the correlation between the remaining mass of fruiting structures and the duration of incubation of the mesh bag.

$$M_t / M_0 = e^{-kt}$$

Where M_0 represents the initial dry mass, M_t denotes the dry mass that remains at time t, and k signifies the decay constant, which is measured in years.

Mean residence time was calculated using the equation as below:

$$MRT = 1/k$$

Meteorological data

The meteorological data for the selected districts were obtained from the Pakistan Meteorological Department observatories at Sukkur, Sakrand, and Tandojam. The average monthly maximum temperature (°C) was documented in Ghotki district, followed by Sakrand and Tandojam districts, and the average minimum temperature (°C) was noted in Tandojam, followed by Sakrand and Ghotki during the years 2020 and 2021, respectively. In June 2020, Ghotki recorded an average maximum temperature of 46°C, while Tandojam reported an average minimum temperature of 27°C in August 2021. The monthly average maximum rainfall recorded in Tandojam was 77.8 mm in August 2020 and 41.9 mm in July 2021. The average humidity (%) was documented from Tandojam, succeeded by Sakrand and Ghotki. The average monthly maximum humidity, recorded at 63% and 58%, was seen in Tandojam during August 2020 and July 2021. The average monthly minimum humidity (15% and 15%) was recorded in the Ghotki district during May 2020 and April 2021 (Figure 2 and Figure 3).

Experimental design

The experiment was laid out using completely randomized design (CRD) with a factorial arrangement to study the decomposition of cotton fruiting structures under changing environmental conditions across three distinct locations in Sindh Province (CRS-Ghotki, CCRI-Sakrand and SAU, Tandojam). The design included two factors: Factor A (locations 3) and Factor B (Fruiting structures 4: squares, flowers, leaves and their mixture), total 12 treatment combinations, each replicated three times. At each location, treatments were randomly assigned to decomposition units (mesh bags).

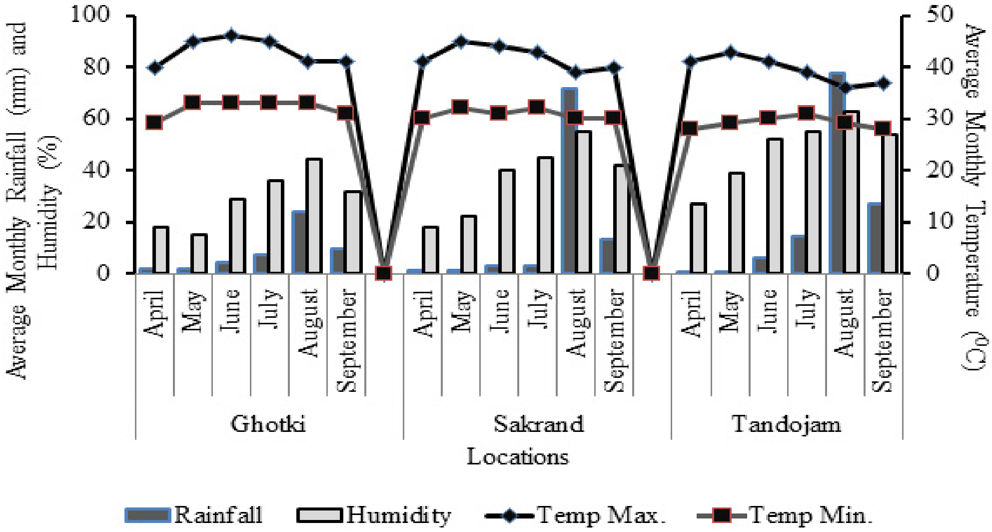

Figure 2: *Average monthly rainfall (mm), relative humidity (%), and temperature (°C) recorded from April to September 2020 at three cotton-growing locations (Ghotki, Sakrand, and Tandojam). Rainfall and humidity are plotted on the primary (left) y-axis, while maximum and minimum temperatures are plotted on the secondary (right) y-axis.*

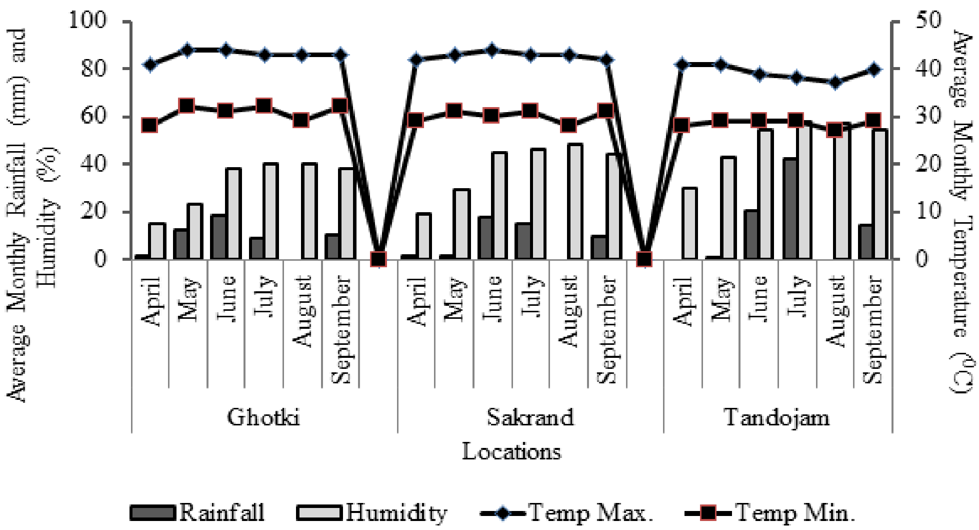

Figure 3: *Average monthly rainfall (mm), relative humidity (%), and temperature (°C) recorded from April to September 2021 at three cotton-growing locations (Ghotki, Sakrand, and Tandojam). Rainfall and humidity are plotted on the primary (left) y-axis, while maximum and minimum temperatures are plotted on the secondary (right) y-axis.*

Data measured

Mass loss, K-rate, mean residence time (Jamro *et al*., 2015), total carbon, nitrogen, carbon to nitrogen ratio and nutrients (NPK) availability (Ryan *et al*., 2001) were measured from the selected locations.

Statistical analysis

The factorial analysis of variance (as per experimental design given above) was performed using statistical software (Statistix 9.1). All the data were subjected to ANOVA analysis. An α value of 0.05 was used to indicate significant differences in all analyses. Pearson correlation was performed among mass loss, K-rate, mean residence time and environmental variables.

Results

Soil physico-chemical properties of three locations, CRS-Ghotki, CCRI-Sakrand, and SAU Tandojam, for the years 2020 and 2021 presented in Table 2, the results indicated that the texture of the soil across all three locations remained relatively consistent over the two years, with sandy clay loam predominating in CRS-Ghotki and CCRI-Sakrand, and loam in SAU Tandojam. Regarding electrical conductivity (EC), there were fluctuations observed across locations and years. In CRS-Ghotki, EC increased from 2.73 dSm^{-1} in 2020 to 3.65 dSm^{-1} in 2021, indicating a rise in salt concentration. In CCRI-Sakrand, EC decreased from 5 dSm^{-1} in 2020 to 4.8 dSm^{-1} in 2021, suggesting a slight reduction in salinity. Similarly, in SAU Tandojam, EC increased marginally from 2 dSm^{-1} in 2020 to 2.4 dSm^{-1} in 2021. The pH levels of the soil in all three locations remained within the alkaline range throughout both years. While minor fluctuations were observed, the overall pH values were relatively stable. Organic matter content varied slightly across locations and years but generally remained within a narrow range. SAU Tandojam exhibited the highest organic matter content compared to the other locations. Nitrogen content also showed minor fluctuations across locations and years, with values generally consistent within each location. Available phosphorus levels varied across locations and years. Notably, CCRI-Sakrand exhibited the highest levels of available phosphorus in both 2020 and 2021. Extractable potassium levels fluctuated across locations and years, with some locations experiencing increases while others showed decreases. SAU Tandojam had relatively stable extractable potassium levels over the two years.

Overall, the results indicate some variability in soil physico-chemical properties across locations and years, highlighting the importance of monitoring and managing these properties for sustainable agricultural practices. Further research may be needed to understand the factors driving these fluctuations and their implications for crop production and soil health.

Shedding of fruiting structures (leaves, squares, flowers) at three locations (CRS-Ghotki, CCRI-Sakrand, SAU, Tandojam)

The data regarding the shedding of fruiting structures (leaves, squares, flowers) at three locations (CRS-Ghotki, CCRI-Sakrand, SAU, Tandojam) presented in Figure 4. At CRS-Ghotki, shedding of cotton fruiting structures declined from 2020 to 2021. In 2020, plants shed 1485 kg ha^{-1} of leaves, 256 kg ha^{-1} of squares, and 501 kg ha^{-1} of flowers, total biomass from the combined shedding of leaves, squares, and flowers was 2602 kg ha^{-1}. In 2021, shedding decreased to 1720 kg ha^{-1} of leaves, 228 kg ha^{-1} of squares, and 460 kg ha^{-1} of flowers, with a total biomass loss of 2408 kg ha^{-1}. These values indicated an overall reduction in the shedding of leaves, squares, and flowers in the second year. At CCRI-Sakrand, the shedding of cotton fruiting structures showed a significant

Table 2: *Soil physico-chemical properties of three locations for the year 2020 and 2021*

Properties	CRS-Ghotki		CCRI-Sakrand		SAU Tandojam	
	2020	2021	2020	2021	2020	2021
Texture	Sandy clay loam	Sandy clay loam	Loam	Loam	Loam	Loam
Electrical conductivity (dS/m)	2.73	3.65	5	4.8	2	2.4
pH (1:1)	8.7	8.8	8.4	8.6	8.2	8
Organic matter (%)	0.64	0.60	0.62	0.68	0.72	0.67
Nitrogen (%)	0.13	0.12	0.12	0.14	0.14	0.13
AB-DTPA extractable phosphorus (mg/Kg)	2	3.1	10.1	9.8	6.8	7.2
Extractable potassium (mg/Kg)	180	196	324	344	198	185

increase from the years 2020 and 2021. In 2020, the plants shed 945 kg ha^{-1} of leaves, 373 kg ha^{-1} of squares, and 369 kg ha^{-1} of flowers. By the year 2021, these figures escalated to 1068, 468, and 417 kg ha^{-1}, respectively, the total biomass shed of 1953 kg ha^{-1}. The increased trend in the shedding of leaves, squares, and flowers indicated that the conditions were less favorable in the second year. At SAU, Tandojam, the levels of shedding remained relatively consistent over the two year period, with only slight reductions observed in 2021. In 2020, cotton plants shed 1528 kg ha^{-1} of leaves, 184 kg ha^{-1} of squares, and 256 kg ha^{-1} of flowers, the total biomass shed 1968 kg ha^{-1}. In 2021, these figures experienced a minor decline to 1500, 161, and 225 kg ha^{-1}, respectively, leading to an overall biomass shed 1885 kg ha^{-1}.

Mass loss (%) in CRS-Ghotki, CCRI-Sakrand, and SAU, Tandojam

A comparison of mass loss percentages among squares, flowers, leaves, and mixed residues at CRS-Ghotki, CCRI-Sakrand, and SAU Tandojam (Figure 5) revealed consistent trends during the 2020 and 2021 periods, although there were notable site-specific differences in the decomposition rates and extents. At CRS-Ghotki, the mass loss was significantly high throughout both years, with averages of over 65% for

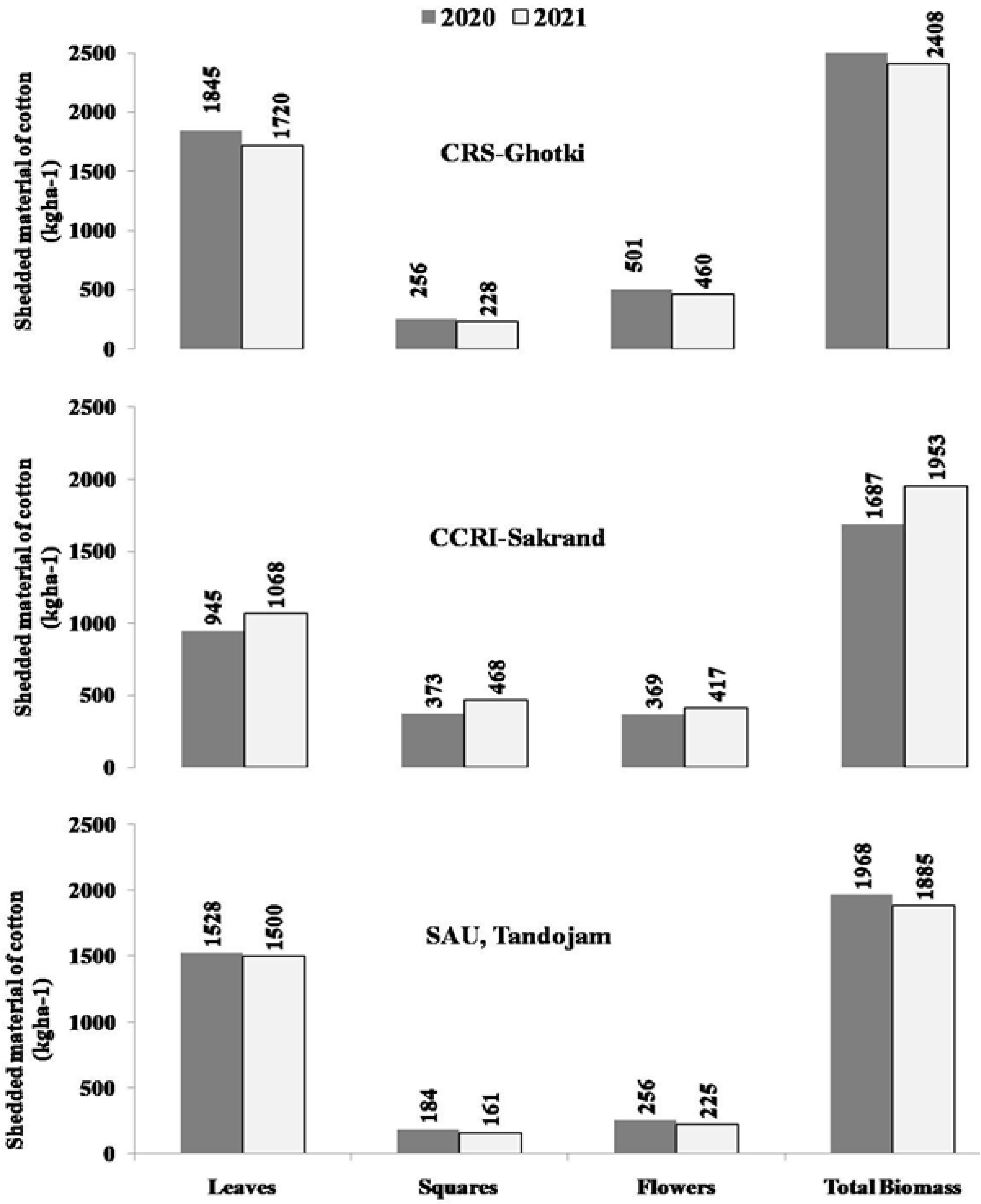

Figure 4: *Shedding of fruiting structures (squares, flowers, leaves) during 2020 and 2021 at three locations*

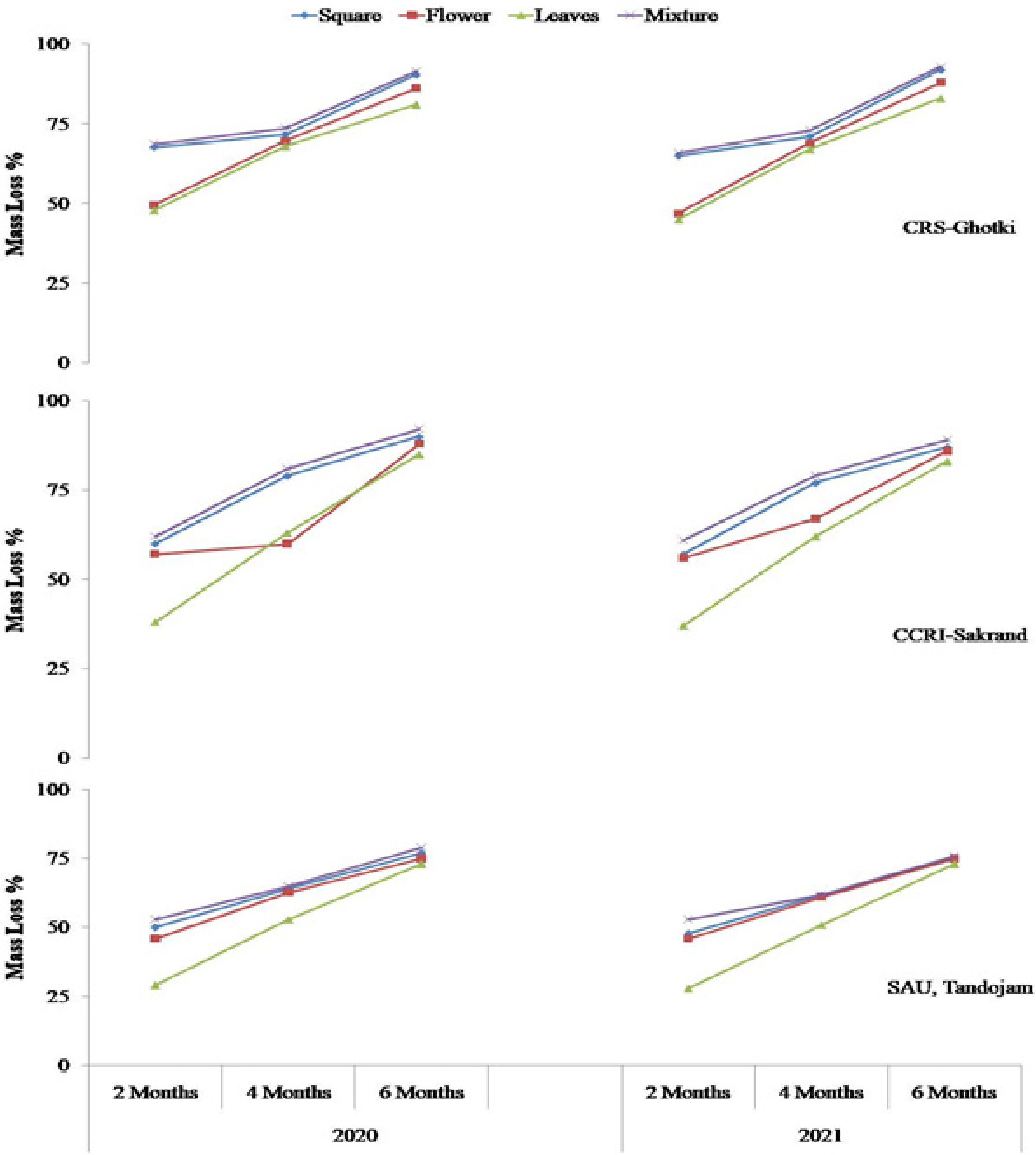

Figure 5: *Mass loss % in different periods during the 2020 and 2021 at three locations*

squares, 50% for flowers, and 45% for leaves recorded by the end of each interval, showing only minor fluctuations from year to year. In CCRI-Sakrand, there was a clear increased trend in mass loss over both years, in a notable 85 to 92% loss across all residues after six months. The early intervals of 2021 showed slightly reduced percentages, but the final values were quite comparable to those from 2020. SAU Tandojam also demonstrated a steady increased in decomposition, though the initial months recorded slightly lower percentages (29 to 53% after two months in 2020), which then increased rise to 73 to 79% at the six-month mark. In 2021, the losses during the early periods were marginally less, yet by the six-month point, mass loss stabilized at similar levels to the previous year.

K-Rate in CRS-Ghotki, CCRI-Sakrand, and SAU, Tandojam

Figure 6 showed consistent patterns in K-rate values across all three locations, with declines over time (2, 4, and 6 months) and minimal year to year variation. At CRS-Ghotki, K-rates for squares, flowers, leaves, and mixtures were higher at the 2-month interval in both

2020 and 2021 and steadily decreased by 6 months, reflected reduced decomposition rates over time. A similar trend was observed at CCRI-Sakrand, where all residue types showed pronounced declines from initial values (e.g., squares: 0.46 to 0.04 in 2020; 0.46 to 0.03 in 2021). SAU Tandojam followed the same pattern, with high early period K-rates (e.g., squares: 0.58 in 2020) that dropped substantially by 6 months. Overall, the data confirmed a uniform decline in decomposition rates across sites, residue types, and years.

Mean residence time (MRT) in CRS-Ghotki, CCRI-Sakrand, and SAU, Tandojam

Figure 7 presented the mean residence time (MRT) for squares, flowers, leaves, and mixtures across CRS-Ghotki, CCRI-Sakrand, and SAU Tandojam for 2020 and 2021. At CRS-Ghotki, MRT values showed a stable, gradual increased over time in both years, with squares rising from about 2.7 (2 months) to over 10 (6 months) and flowers increased from ~1.7 to ~6.5, reflecting consistent residue persistence. At CCRI-Sakrand, MRT values increased more sharply across intervals indicated longer residue retention. Squares showed the highest MRTs, rising from around 2.2 at 2 months to over 10 to 11 months at 6 months in both years, while flowers, leaves, and mixtures followed a similar upward pattern with slightly higher values in 2021. At SAU Tandojam, MRT values showed moderate variation without a strong directional trend.

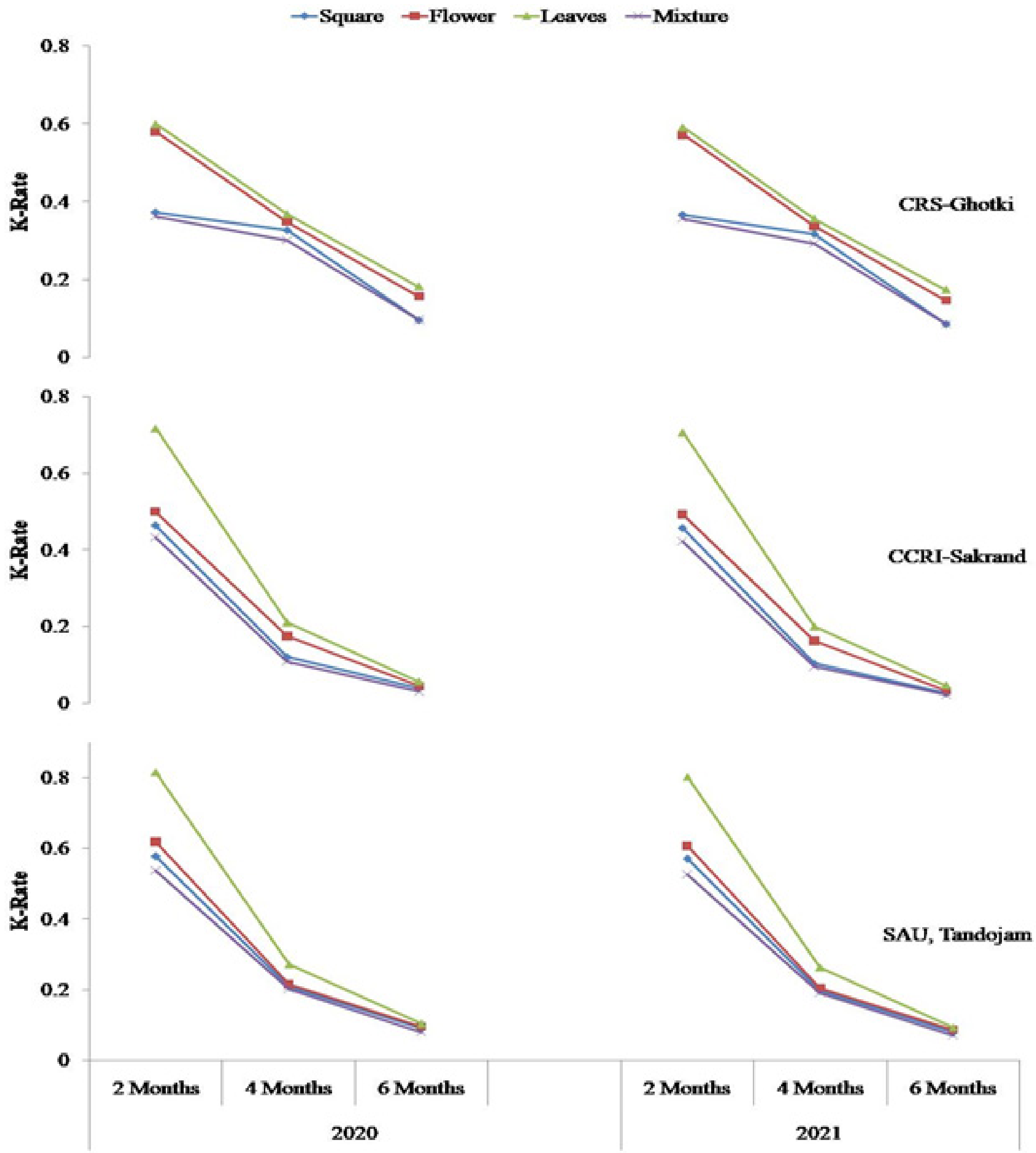

Figure 6: *K-Rate in different periods during the 2020 and 2021 at three locations*

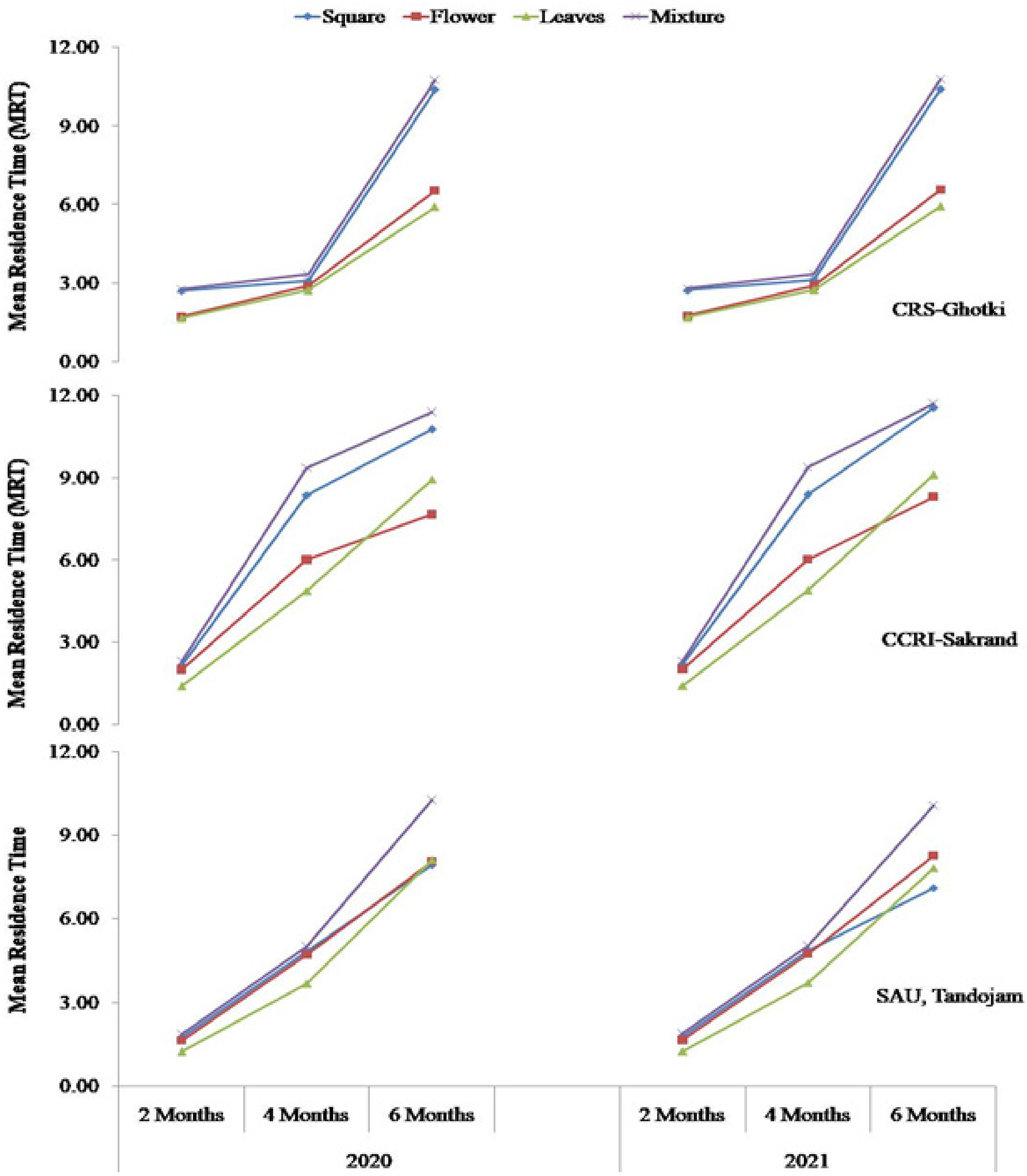

Figure 7: *Mean residence time (MRT) in different periods during the 2020 and 2021 at three locations.*

In both years, squares increased from approximately 1.7 to 1.8 at 2 months to 7 to 8 months at 6 months, with flowers, leaves, and mixtures displaying similar but slightly lower or fluctuated values. Overall, residue persistence remained moderate and relatively stable across years.

Total carbon content (%), total nitrogen content (%), C:N ratio, phosphorus content (%), potassium content (%) in the fruiting structure and leaves of CRS-Ghotki

Carbon, nitrogen, C:N ratio, phosphorus, and potassium levels in CRS-Ghotki fruiting structures and leaves summarized in Table 3. Total carbon showed significant effects ($p<0.05$) in both years, with leaves consistently highest (78.0% in 2020; 76.33% in 2021). Total nitrogen also differed significantly ($p<0.05$), again peaking in leaves (3.37% in 2020; 3.10% in 2021). The C:N ratio varied significantly across structures, with flowers and squares highest in 2020 (29.26 and 28.49), and squares highest in 2021 (26.33). Phosphorus percentages also differed, with flowers highest in 2020 (0.236%) and squares highest in 2021 (0.216%). Potassium showed significant variation, with leaves recording the greatest levels in both years. Overall, nutrient concentrations varied among squares, flowers, leaves, and mixed samples,

Table 3: *Total carbon (%), total nitrogen (%), C:N ratio, phosphorus (%), potassium (%) in the fruiting structure and leaves of CRS-Ghotki in 2020 and 2021.*

Fruiting structures	Total carbon (%)	Total nitrogen (%)	C:N Ratio	Phosphorus (%)	Potassium (%)
2020					
Square	75 (2.08)A	2.63 (0.09)B	28.49 (0.40)AB	0.2266 (0.0088)AB	1.83 (0.02)B
Flower	73 (2.08)AB	2.5 (0.06)B	29.26 (0.59)A	0.2366 (0.0088)A	1.99 (0.07)AB
Leaves	78 (1.45)A	3.37 (0.09)A	23.31 (1.00)C	0.2100 (0.0058)B	2.19 (0.10)A
Mixture	67 (1.45)B	2.73 (0.09)B	24.84 (1.31)BC	0.2033 (0.0067)B	1.92 (0.09)AB
2021					
Square	73.00 (2.08)A	2.43 (0.09)BC	26.33 (0.85)A	0.2066 (0.0088)AB	1.83 (0.07)B
Flower	71.00 (2.08)AB	2.30 (0.06)C	25.35 (0.70)AB	0.2166 (0.0088)A	1.92 (0.04)AB
Leaves	76.33 (1.45)A	3.10 (0.06)A	21.16 (0.18)C	0.1933 (0.0033)AB	2.09 (0.07)A
Mixture	65.66 (1.45)B	2.56 (0.07)B	23.43 (1.16)BC	0.1833 (0.0067)B	1.80 (0.05)B

Means with different upper case letters indicate significant difference.
Values are shown in brackets indicate standard error (n=4)

with leaves generally showed the highest carbon, nitrogen, phosphorus, and potassium, while the C:N ratio peaked in flowers or squares depending on the year.

Total carbon content (%), total nitrogen content (%), C:N ratio, phosphorus content (%), potassium content (%) in the fruiting structure and leaves of CCRI-Sakrand

Table 4 summarized the percentages of total carbon, total nitrogen, C:N ratio, phosphorus, and potassium for CCRI-Sakrand in the years 2020 and 2021. In both years, total carbon was notably highest in leaves, recorded 75.0% in 2020 and 73.33% in 2021, followed by squares, flowers, and mixtures. Total nitrogen also reached its peak in leaves each year, with flowers ranked next in 2020 and mixtures in 2021. The C:N ratio was most pronounced in squares for both years, recorded at 25.82 in 2020 and 23.80 in 2021, followed by flowers, mixtures, and leaves. Consistently, flowers exhibited the highest phosphorus percentages across both years, with squares, mixtures, and leaves following in that order. Additionally, potassium levels were highest in leaves for both years, followed by flowers, squares, and mixtures.

Total carbon content (%), total nitrogen content (%), C:N ratio, phosphorus content (%), potassium content (%) in the fruiting structure and leaves of SAU, Tandojam

The data on total carbon percentage, total nitrogen, C:N ratio, phosphorus percentage, and potassium percentage in the fruiting structure and leaves of SAU, Tandojam, is presented in Table 5. In both 2020 and 2021, leaves had the highest total carbon (73.00% and 73.33%), followed by squares, flowers, and mixtures.

Table 4: *Total carbon (%), total nitrogen (%), C:N ratio, phosphorus (%), potassium (%) in the fruiting structure and leaves of CCRI-Sakrand in 2020 and 2021*

Fruiting structures	Total carbon (%)	Total nitrogen (%)	C:N Ratio	Phosphorus (%)	Potassium (%)
2020					
Square	73 (0.58)A	2.83 (0.09)B	25.82 (0.93)A	0.2166 (0.0088)A	1.70 (0.02)BC
Flower	65 (1.20)B	2.70 (0.06)B	24.33 (0.59)AB	0.2266 (0.0088)A	1.82 (0.07)B
Leaves	75 (1.76)A	3.66 (0.12)A	20.64 (0.20)C	0.2000 (0.0058)AB	2.07 (0.05)A
Mixture	64 (1.45)B	2.86 (0.09)B	22.61 (1.01)BC	0.1800 (0.0100)B	1.65 (0.04)C
2021					
Square	71.00 (0.58)A	2.43 (0.07)B	23.80 (0.85)A	0.2000 (0.0058)AB	1.66 (0.02)C
Flower	63.33 (1.45)B	2.33 (0.07)B	22.30 (0.70)AB	0.2100 (0.0115)A	1.78 (0.04)B
Leaves	73.33 (2.03)A	3.30 (0.15)A	18.86 (0.18)C	0.1833 (0.0033)BC	1.97 (0.03)A
Mixture	62.00 (1.15)B	2.46 (0.03)B	20.36 (1.16)BC	0.1633 (0.0067)C	1.62 (0.04)C

Means with different upper case letters indicate significant difference.
Values are shown in brackets indicate standard error (n=4)

Table 5: *Total carbon (%), total nitrogen (%), C:N ratio, phosphorus (%), potassium (%) in the fruiting structure and leaves of CCRI-Sakrand in 2020 and 2021*

Fruiting structures	Total carbon (%)	Total nitrogen (%)	C:N Ratio	Phosphorus (%)	Potassium (%)
2020					
Square	68 (1.20)A	3.00 (0.06)B	22.90 (0.51)A	0.1833 (0.0120)AB	1.71 (0.05)A
Flower	63 (1.16)B	2.80 (0.12)B	22.66 (0.68)A	0.2000 (0.0058)A	1.72 (0.03)A
Leaves	73 (1.76)A	3.76 (0.15)A	19.54(1.08)A	0.1666 (0.0088)B	1.77 (0.07)A
Mixture	61 (1.53)B	3.06 (0.18)B	20.07 (1.59)A	0.1566 (0.0088)B	1.65 (0.05)A
2021					
Square	68.66 (1.20)A	2.70 (0.06)B	21.10 (0.61)A	0.1666 (0.0088)AB	1.68 (0.05)A
Flower	63.33 (1.76)B	2.53 (0.07)B	20.73 (0.52)A	0.1833 (0.0033)A	1.70 (0.02)A
Leaves	73.33 (1.76)A	3.33 (0.18)A	17.60 (0.72)B	0.1500 (0.0058)BC	1.75 (0.06)A
Mixture	61.00 (1.53)B	2.83 (0.15)B	18.06 (1.16)B	0.1433 (0.0067)C	1.65 (0.06)A

Means with different upper case letters indicate significant difference.
Values are shown in brackets indicate standard error (n=4)

Leaves also consistently had the highest total nitrogen, with mixtures generally second, followed by squares and flowers. C:N ratios varied slightly, with flowers and squares showing the highest values, while mixtures and leaves were lower. Phosphorus percentages were consistently highest in flowers, with squares, mixtures, and leaves following; the exact order varied slightly between years. Potassium showed little variation across categories in both years.

Correlation matrix of decomposition dynamics and environmental factors in cotton fruiting structures

The strongest correlations across the fruiting structures (Leaves, squares, flowers, and mixture) revealed several consistent and biologically meaningful patterns (Table 6). Percent change and decomposition (PC–DC) showed near perfect positive correlations in all fruiting structures (r = 0.93–1.00), indicating a tightly linked structural or phenotypic relationship. Temperature variables were similarly cohesive, with maximum and minimum temperatures (Max T–Min T) exhibited very high correlations (r = 0.97–1.00). Rainfall and humidity also correlated strongly (r = 0.76–0.93), reflected expected moisture related interactions. Nutrient variables showed comparably strong associations: total carbon (TC) and carbon-to-nitrogen ratio (CN) correlated consistently across fruiting structures (r = 0.78–0.88), while total nitrogen (TN) and CN also displayed strong relationships (r = 0.84–0.91), highlighted the strong linkage between CN, carbon levels, and nitrogen availability. Minimum temperature and rainfall correlations were moderately strong in leaves, squares and flowers (r = 0.73–0.84) but weaker in the mixture (r = 0.60), suggested variable temperature precipitation interactions among fruiting structures. Overall, these patterns highlighted stable climatic and nutrient relationships across sampling methods, offered a clearer synthesis than a full assessment of the complete correlation matrices.

Table 6: *Correlation matrix of decomposition dynamics and environmental factors in cotton fruiting structures*

Parameter pairs	Leaves	Squares	Flowers	Mixture
Percent change – Decomposition	0.99	0.98	0.93	1.00
Maximum temp. – Minimum temp.	0.97	0.98	0.99	1.00
Total carbon – C:N ratio	0.78	0.78	0.86	0.88
Rainfall – humidity	0.92	0.87	0.93	0.76
Minimum temp. – rainfall	0.84	0.77	0.73	0.60*
Total nitrogen – C:N ratio	0.91	0.91	0.86	0.84

* *Below threshold; optional*

Discussion

The decomposition and shedding dynamics of cotton fruiting structures (squares, flowers, leaves) showed considerable variation under changing environment of Sindh Province and over two growing seasons (2020 and 2021). The observed spatial and temporal fluctuations reflect the interactive effects of environmental conditions and agronomic practices and the genetic attribute of the cotton variety. Such variations were crucial to understanding residue management, nutrient cycling, and the sustainability of cotton based agro-ecosystems under changing climatic conditions.

At CRS-Ghotki, fruiting-structure shedding declined from 2020 to 2021, suggesting improved environmental or management conditions in the latter year. In contrast, shedding increased at CCRI-Sakrand, indicating possible stress or unfavorable environmental shifts, while SAU-Tandojam remained relatively stable. These observations align with previous studies (Tariq *et al*., 2017; Majeed *et al*., 2021), which highlight temperature extremes and nutrient status as key regulators of shedding. High temperature episodes, in particular, can exacerbate flower shedding (Wang *et al*., 2020).

Mass-loss dynamics of squares, flowers, leaves, and mixed residues also showed site-specific trends. CRS-Ghotki exhibited reduced mass loss in 2021, CCRI-Sakrand experienced an increase, and SAU-Tandojam displayed slight declines. These variations correspond to the well-established relationship between warmer thermal regimes and accelerated microbial decomposition (Naeth *et al*., 2011). The correlation matrix in this study further confirmed that maximum temperature was strongly and positively associated with the decomposition rate, demonstrating its central regulatory role across locations. This observation aligns with current findings showed that temperature sensitivity remained one of the most consistent predictors of litter decay across climate gradients (Fierer *et al*., 2021; Wang *et al*., 2023). By merging these findings, it is clear that temperature primarily dictated both fruiting-structure shedding and residue decomposition, though local management and short-term microclimatic conditions modulated responses. Similar site level modulation has been reported where irrigation schedules, canopy shading, and soil surface conditions interact with temperature to drive residue decomposition in semi-arid agro-ecosystems (Nunes *et al*., 2020).

The decomposition rate constant (k) declined over time for all fruiting structures and environments, reflecting the transition from rapid decay of soluble compounds to slower degradation of recalcitrant materials such as lignin and waxes (Berg and McClaugherty, 2003; Cotrufo *et al*., 2013). Correspondingly, mean residence time (MRT) generally increased, indicating prolonged persistence of residues during later decomposition stages. This pattern is consistent with findings that MRT is strongly governed by substrate quality, with high lignin:N or C:N ratios leading to slower microbial turnover and longer litter residence times (Freschet *et al*., 2020; Li *et al*., 2022). Leaves consistently decomposed faster, showing lower MRT values due to their higher nutrient concentrations and lower lignin content, whereas squares and mixed residues persisted longer because of their higher C:N ratios and structurally dense tissues. Recent work has similarly shown that nutrient rich, structurally soft tissues with low lignin concentrations exhibited accelerated mineralization compared with recalcitrant reproductive or woody residues (Alvarez-Uria *et al*., 2021; Wang *et al*., 2023).

Chemical analyses supported these patterns. Leaves contained the highest total carbon, nitrogen, phosphorus, and potassium across both seasons, consistent with their role in photosynthesis and nutrient acquisition (Melillo *et al*., 1982). In contrast, squares and flowers exhibited lower nutrient levels but higher C:N ratios, which contributed to slower microbial breakdown. High C:N ratios, especially values exceeding 30, are known to limit microbial activity and retard decomposition (Melillo *et al*., 1982). Flowers also showed relatively high phosphorus concentrations particularly in 2021 reflecting the nutrient requirements of reproductive development. Potassium remained consistently high in leaves and showed limited variation among other structures, supporting observations that K is frequently remobilized from reproductive tissues to sustain leaf function (Gupta and Solanki, 2013). Recent studies further confirmed that climate and litter quality (C:N ratio) remain among the strongest predictors of litter decomposition and nutrient release. For example, a global scale meta-analysis found that decomposition rate (k) increases with higher temperatures, greater nutrient concentrations, and lower C:N or lignin content (Zhang *et al*., 2008; Zhao *et al*., 2025).

Correlations among decomposition metrics, environmental factors, and residue chemistry reinforced these conclusions. Faster decomposition corresponded to shorter MRTs, while higher C:N ratios were associated with slower breakdown and longer persistence (Austin and Vitousek, 2000). Maximum temperatures exhibited strong positive relationships with both percent mass change and decomposition rate, consolidating their role as primary drivers of residue decay. These findings are consistent with recent global assessment showed that warmer thermal regimes accelerated microbial mineralization and increase decomposition rate constants across diverse litter types (Bradford *et al*., 2019; Suseela and Tharayil, 2021). Meanwhile, rainfall and humidity showed weaker and more variable associations, likely due to irrigation inputs and the episodic nature of precipitation in semi-arid systems. Similar patterns were reported in arid and semi-arid agro-ecosystems where moisture pulses rather than mean rainfall, governed decomposition dynamics (Berdugo *et al*., 2020). As Prescott (2010) noted, in water-limited environments, decomposition often becomes constrained by moisture more than temperature unless supplemental irrigation is provided.

These findings carried important implications for soil health management in cotton systems. Faster-decomposing materials such as leaves can be influenced to enhance short-term nutrient availability, while slower decomposing residues like squares and mixed fractions contributed to longer-term soil organic matter buildup. Understanding site-specific MRT and k-rate patterns can guide decisions on tillage timing, residue retention, and integration of intercrops or cover crops that complement residue breakdown. By aligning residue management with decomposition dynamics, farmers can improve nutrient-use efficiency, reduce losses, and enhance soil structure, thereby strengthening the resilience and productivity of cotton based agro-ecosystems.

Conclusions and Recommendations

The research indicated that the shedding and decomposition of cotton fruiting structures (including leaves, squares, flowers, and their combinations) differed by location and season, significantly affected by environmental factors, the quality of residues, and nutrient content. Leaves, which contain higher concentrations of nutrients, decomposed rapidly, whereas squares and flowers, characterized by higher C:N ratios, persisted longer and broke down more slowly, thereby influenced soil nutrient cycling and carbon dynamics. Temperature was identified as the primary factor driving decomposition, while rainfall and humidity exhibited weaker, yet context-dependent influences. These results emphasized the necessity of managing cotton residues to enhance soil fertility and sustainability. It showed that shed residues, especially nutrient-dense leaves, into the soil to boost organic matter, while managing high C:N residues like squares and flowers with nutrient supplements to hasten their breakdown. The implementation of the 4R nutrient stewardship strategy, along with climate-smart practices such as efficient irrigation and resilient cotton varieties, can mitigate premature shedding and enhance residue quality. Furthermore, conservation agriculture techniques, including residue retention and reduced tillage, should be promoted to improve soil carbon sequestration, while additional research on microbial interactions and the long-term effects of residue decomposition in the context of climate change is crucial for sustainable cotton production systems. Future studies should also integrate microbial community dynamics and carbon modeling approaches to better predict decomposition patterns and soil carbon outcomes.

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Novelty Statement

This research represents the initial thorough evaluation of the *in-situ* shedding and decomposition processes of cotton fruiting structures (including leaves, squares, and flowers) in response to the fluctuating environmental conditions present in Sindh, Pakistan. By combining data on biomass loss, decomposition rate (k), mean residence time (MRT), and nutrient composition (C, N, P, K) from various locations and seasons, this study offers innovative perspectives on how the quality of residues and climate interactions influence nutrient cycling and soil carbon dynamics within cotton-based agro-ecosystems. The results of this study lay a scientific foundation for effective residue management and climate-smart nutrient strategies aimed at improving soil fertility and sustainability in cotton production systems.

Authors' Contribution

Abdullah Keerio: Carried out entire research work,

trials, management, research paper writeup..
Ghulam Murtaza Jamro: Idea, Layout, design of experiments, supervision of research work, editing of manuscript
Zia-ul-hassan and Pir Ahmed Naqi Shah: Data analysis and in-terpretation of results
Javaid Ahmed Shah: Design in layout, samples analysis and interpretation of results

Generative AI or AI assisted technology statement
The authors declare that no generative AI was used in the development of this manuscript.

Conflict of interest
The authors have no conflict of interest.

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