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Influence of source manipulation and nitrogen regimes on phenological, canopy and panicle traits of Sorghum

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Abstract

Sorghum productivity during the reproductive phase depends strongly on the maintenance of an effective photosynthetic canopy and adequate nutrient availability. The present study evaluated the effects of source manipulation through graded leaf defoliation and nitrogen management on phenological development, canopy characteristics and panicle architecture of sorghum during 2023-24 and 2024-25. Five source-manipulation treatments and four nitrogen regimes were evaluated, with observations recorded for days to anthesis, days to maturity, number of leaves, leaf area, leaf area index (LAI), panicle length and panicle circumference. Days to anthesis remained largely unaffected by either defoliation or nitrogen treatment, reflecting the fact that source manipulation was imposed at anthesis. In contrast, increasing defoliation progressively shortened crop duration and reduced canopy development. The most severe defoliation treatment (F5) consistently produced the lowest number of leaves, leaf area and LAI, with the response evident at both 10 and 25 days after treatment. Nitrogen application produced an opposite response, with the higher split nitrogen regime (N4) maintaining greater canopy development and delaying maturity. Panicle architecture followed a similar pattern, with increasing defoliation reducing panicle length and circumference, whereas higher nitrogen supply generally enhanced both traits. The contrasting responses of the intact-canopy and severe-source-limitation treatments were consistent across the two growing seasons. Overall, the findings demonstrate that maintenance of the upper photosynthetic canopy after anthesis, together with appropriately timed nitrogen management, is important for sustaining crop duration, canopy development and panicle architecture in sorghum.

Keywords: *Sorghum bicolor*; source manipulation; leaf defoliation; nitrogen management; leaf area index; phenology; panicle architecture; canopy development

Introduction

Sorghum (*Sorghum bicolor* L. Moench) has a strong capacity to maintain productivity under variable growing conditions, yet grain development ultimately depends on the amount and persistence of photosynthetically active leaf area during the reproductive phase (Seebauer *et al.*, 2010; Shahrudin *et al.*, 2014) ^[15, 17]. As a C4 cereal, sorghum has a high photosynthetic capacity, making the maintenance of an effective canopy particularly important for assimilate production and subsequent partitioning towards the developing panicle (Ueno and Fuchikami, 2020; Yin and Struik, 2015) ^[18, 20]. Leaf area index is therefore not merely a measure of canopy size, but an important determinant of the crop's source capacity (Mujahid *et al.*, 2020; Nanja Reddy *et al.*, 2019) ^[9, 10].

The contribution of individual leaves becomes especially relevant after anthesis. The flag leaf, penultimate leaf and upper canopy remain important sources of assimilates during reproductive development, and their removal provides a useful experimental approach for imposing defined levels of source limitation (Jalilian and Delkhoshi, 2013; Raza *et al.*, 2020; Serrago *et al.*, 2013) ^[14, 6, 16]. Increasing defoliation can reduce leaf number, leaf area and LAI, potentially altering the duration of crop development and limiting assimilate availability for panicle growth (Xiao-li *et al.*, 2022) ^[19]. The present experimental observations confirm that progressively greater defoliation substantially reduced LAI, with the strongest reduction occurring when the flag leaf,

penultimate leaf and 30% of upper-canopy leaves were removed. leaf expansion and canopy development, while its availability during flowering and grain development can help sustain photosynthetically active leaf area (Hawkesford *et al.*, 2012; Arduini *et al.*, 2006) ^[1, 4]. In the present study, split nitrogen application, particularly the higher nitrogen regime distributed across sowing, flowering and grain development, increased LAI relative to the control. Despite the established importance of canopy maintenance and nitrogen nutrition, the response of phenological development and panicle architecture to their combined manipulation has received comparatively less attention in a single experimental framework. Therefore, the present study evaluated the effects of graded leaf defoliation and nitrogen regimes on days to anthesis, days to maturity, number of leaves, leaf area, LAI, panicle length and panicle circumference in sorghum. The objective was to determine how changes in source capacity during reproductive development are reflected in crop phenology, canopy structure and panicle development.

2. Materials and Methods

2.1 Experimental site

The field experiment was conducted during two consecutive *Rabi* seasons, 2023-24 and 2024-25, at the research farm of the Department of Plant Physiology, College of Agriculture, Indira Gandhi Krishi Vishwavidyalaya (IGKV), Krishak Nagar, Raipur, Chhattisgarh, India.

2.2 Plant material and experimental conditions

Sorghum (*Sorghum bicolor* L. Moench) variety PKV-Kranti (SPV-1201, Ringani) was used as the experimental material. The crop was grown under field conditions at the experimental site during both growing seasons. The crop was planted at a spacing of 45 cm × 15 cm, and individual experimental plots measured 2.2 m × 1.8 m. The total experimental area was approximately 364 m². The crop received the recommended fertilizer dose of 90:45:45 kg ha⁻¹ of N:P₂O₅:K₂O, with nitrogen application modified according to the experimental treatments. All other crop-management practices were maintained uniformly across treatments following the recommended agronomic practices for sorghum. Source-manipulation treatments were imposed at the anthesis stage through selective mechanical removal of leaves.

2.3 Experimental design and treatments

The experiment consisted of two factors: source manipulation through graded leaf defoliation and nitrogen management. Four nitrogen regimes (N1-N4) were evaluated in combination with five source-manipulation treatments (F1-F5), giving a factorial treatment structure. The detailed structure and description of the nitrogen regimes and source-manipulation treatments are presented in Table 1.

2.4 Nitrogen treatments

Four nitrogen regimes, designated N1 to N4, were imposed. N3 consisted of 100% recommended dose of fertilizer (RDF) applied in two equal splits at sowing and flowering, whereas N4 consisted of 150% RDF applied in three equal splits at sowing, flowering and grain development. The supplied Results chapter does not provide sufficiently explicit descriptions of N1 and N2 beyond

their treatment codes; accordingly, their exact fertilizer rates have not been inferred.

2.5 Measurement of phenological traits

2.5.1 Days to anthesis

Days to anthesis was recorded as the number of days required for the crop to reach anthesis. Because source manipulation was imposed at anthesis, this trait was used primarily to characterize the timing of the treatment stage rather than as a post-treatment response. The recorded values were approximately 64-67 days across treatment combinations in both seasons.

2.5.2 Days to maturity

Days to maturity was recorded as the number of days from establishment of the crop until physiological maturity. The trait was assessed in both growing seasons to determine whether reduction in photosynthetic source capacity during reproductive development altered the duration of crop development. The supplied results indicate that both defoliation and nitrogen treatments significantly influenced maturity duration.

2.6 Measurement of canopy traits

2.6.1 Number of leaves

The number of leaves plant⁻¹ was recorded at 10 and 25 days after treatment (DAT). The observations were used to quantify the persistence of the leaf canopy following source manipulation. Treatment-level data for both seasons are available in the experimental dataset.

2.6.2 Leaf area

Leaf area was measured at 10 and 25 DAT to determine the effect of source manipulation and nitrogen supply on the remaining photosynthetically active canopy. Measurements were recorded on a plant basis and expressed as cm² plant⁻¹. The Results chapter confirms that leaf area was assessed at these two observation dates in both seasons.

2.6.3 Leaf area index

Leaf area index (LAI) was determined at 10 and 25 DAT as an indicator of canopy development following source manipulation. LAI was used to integrate changes in leaf number and leaf area into a measure of canopy size. The study recorded a consistent reduction in LAI with increasing defoliation and an increase under higher and split nitrogen application.

2.7 Measurement of panicle traits

2.7.1 Panicle length

Panicle length was measured at physiological maturity in both growing seasons. The trait was used to assess the effect of altered source availability and nitrogen nutrition on reproductive structural development.

2.7.2 Panicle circumference

Panicle circumference was recorded at physiological maturity as an additional measure of panicle architecture. Measurements were expressed in centimetres. The treatment data show a consistent decline in panicle circumference with increasing defoliation and an improvement under enhanced nitrogen supply.

2.8 Statistical analysis

The observations recorded for each trait were subjected to analysis of variance (ANOVA) using OPSTAT software. Treatment means were compared using the critical difference (CD) at the 5% probability level, and the standard error of the

mean and coefficient of variation were reported for the respective factors and their interaction. The statistical summaries in the supplied tables separately report Factor A, Factor B and Factor A $\times$ B interaction effects for each growing season.

3. Results

3.1 Phenological development

3.1.1 Days to anthesis

Days to anthesis showed very little variation among the source-manipulation and nitrogen treatments in either season. The analysis of variance indicated that the effects of defoliation, nitrogen and their interaction were non-significant, which is consistent with the fact that the source-manipulation treatments were imposed at anthesis. In 2023-24, the mean days to anthesis ranged from 65.17 days under F5 to 65.42 days under F1. Similarly, in 2024-25, the corresponding values ranged from 66.16 days under F4 and F5 to 66.41 days under F2 and F3. The treatment-wise response of days to anthesis across nitrogen and source-manipulation regimes is presented in Table 2A.

Nitrogen treatments also produced only minor differences. In the first season, N4 recorded 65.13 days to anthesis, compared with 65.67 days under N1, while in the second season the treatment means ranged from 66.00 to 66.86 days. At the treatment-combination level, N4 $\times$ F1 recorded the lowest value in 2023-24 (64.67 days), whereas N1 $\times$ F5 recorded 66.00 days. In 2024-25, the corresponding values were 66.00 and 66.66 days, respectively.

3.1.2 Days to maturity

In contrast to anthesis, days to maturity responded strongly to both source manipulation and nitrogen supply. The analysis of variance showed significant effects of both factors in both seasons. Increasing the severity of defoliation progressively shortened the time required to reach physiological maturity. In 2023-24, F5 recorded the earliest maturity at 114.08 days, followed by F4 at 119.16 days, whereas the control F1 required 125.58 days. A similar pattern occurred in 2024-25, where F5 matured in 113.75 days, compared with 117.83 days under F4 and 126.33 days under F1.

Nitrogen produced the opposite response. Increasing nitrogen supply, particularly under the split application regime, prolonged crop duration. In 2023-24, N4 recorded 124.46 days to maturity, followed by N3 with 121.60 days, compared with 117.26 days under the control. In the second season, N4 and N3 required 124.73 and 121.93 days, respectively, whereas the control matured in 116.66 days.

The interaction further emphasized the contrasting effects of the two factors. The latest maturity occurred under N4 $\times$ F1, with 129.33 days in 2023-24 and 131.33 days in 2024-25. Conversely, N1 $\times$ F5 matured earliest, requiring only 111.33 and 110.33 days in the respective seasons. The effect of source manipulation and nitrogen regimes on days to maturity during both growing seasons is presented in Table 2B. Taken together, the relatively stable anthesis timing and the contrasting effects on maturity indicate that source manipulation and nitrogen regimes primarily influenced post-anthesis crop duration rather than the onset of flowering. This overall phenological response is illustrated in Figure 1.

3.2 Canopy development

3.2.1 Number of leaves

The number of leaves plant⁻¹ was significantly affected by both defoliation and nitrogen supply at 10 and 25 DAT in both seasons. Increasing defoliation intensity resulted in a progressive reduction in leaf number. During 2023-24, the F5 treatment recorded only 4.8 leaves plant⁻¹ at 10 DAT and 4.0 leaves plant⁻¹ at 25 DAT,

compared with 8.7 and 8.1 leaves under the control F1. F4 showed an intermediate response, with 6.0 and 5.8 leaves at the two observation dates.

The same pattern was observed during 2024-25. F5 resulted in the greatest reduction, with mean values of 5.1 and 4.5 leaves plant⁻¹ at 10 and 25 DAT, respectively, compared with 9.9 and 8.8 leaves under F1.

Nitrogen partially offset this reduction in canopy development. Across both observation dates and seasons, N4 produced the highest leaf number, with mean values of approximately 8.4 leaves at 10 DAT and 7.6 leaves at 25 DAT, followed by N3, whereas the control nitrogen regime recorded 7.0 and 6.2 leaves, respectively.

The strongest treatment contrast occurred under N4 $\times$ F1, which produced 10.6 leaves at 10 DAT and 9.3 leaves at 25 DAT in 2024-25. In contrast, N1 $\times$ F5 resulted in only 4.0 leaves at both observation stages. The effect of source manipulation and nitrogen regimes on the number of leaves plant⁻¹ at 10 and 25 DAT is presented in Table 3A.

3.2.2 Leaf area

Leaf area followed a pattern closely associated with the changes in leaf number. Significant effects of both defoliation and nitrogen were observed at 10 and 25 DAT in both seasons. In 2023-24, the control F1 recorded the highest leaf area, reaching 448.5 cm² plant⁻¹ at 10 DAT and 434.6 cm² plant⁻¹ at 25 DAT. Progressive source removal reduced leaf area, with F5 recording only 355.0 and 319.7 cm² plant⁻¹ at the respective stages. The reduction was also evident in the second season. F5 recorded 329.7 cm² plant⁻¹ at 10 DT and 286.0 cm² plant⁻¹ at 25 DAT, compared with 446.0 and 394.3 cm² plant⁻¹ under F1. Nitrogen enhanced leaf area in both seasons. In 2023-24, N4 produced the highest mean leaf area, 424.3 cm² plant⁻¹ at 10 DAT and 424.4 cm² plant⁻¹ at 25 DAT, compared with 375.4 and 322.5 cm² plant⁻¹ under the control. The same ranking was observed in 2024-25, where N4 recorded 429.1 and 379.5 cm² plant⁻¹ at 10 and 25 DAT, respectively. At the interaction level, N4 $\times$ F1 produced the largest leaf area in 2023-24, reaching 465.9 cm² plant⁻¹ at 10 DAT and 481.5 cm² plant⁻¹ at 25 DAT, whereas N1 $\times$ F5 recorded only 325.7 and 293.9 cm² plant⁻¹. The effect of source manipulation and nitrogen regimes on leaf area at 10 and 25 DAT is presented in Table 3B.

3.2.3 Leaf area index

LAI responded strongly to source manipulation and nitrogen supply. Increasing defoliation caused a progressive reduction in LAI at both observation dates. In 2023-24, mean LAI under F1 was 0.665 at 10 DAT and 0.614 at 25 DAT, whereas F5 reduced it to 0.526 and 0.474, respectively.

The same trend was observed in 2024-25. F1 recorded the highest LAI, whereas F5 showed the lowest values, particularly at 25 DAT. The minimum treatment combination was consistently N1 $\times$ F5, with LAI values of 0.483 and 0.435 at 10 and 25 DAT in 2023-24 and 0.441 and 0.358 in 2024-25. Nitrogen application increased LAI, with the highest values generally recorded under N4. The strongest interaction was observed under N4 $\times$ F1, which recorded LAI values of 0.690 and 0.713 at 10 and 25 DAT in the first season and 0.745 and 0.641 in the second season. The effect of source manipulation and nitrogen regimes on leaf area index at 10 and 25 DAT is presented in Table 3C. Overall, the canopy traits showed a clear and consistent response: greater source removal reduced leaf number, leaf area and LAI, whereas higher and split nitrogen application maintained a larger canopy. The overall canopy development response to source manipulation and nitrogen regimes is illustrated in Figure 2.

3.3 Panicle architecture

3.3.1 Panicle length

Panicle length was significantly influenced by both source manipulation and nitrogen regime in both seasons. Increasing defoliation progressively reduced panicle length. In 2023-24, mean panicle length declined from 21.27 cm under F1 to 19.37 cm under F5. In 2024-25, the corresponding decline was from 19.36 cm to 15.31 cm. Nitrogen had a positive effect on panicle length. N4 produced the longest panicles, with mean values of 21.66 cm in 2023-24 and 18.33 cm in 2024-25, followed by N3 with 20.56 and 17.84 cm, respectively. The interaction between nitrogen and defoliation was evident in both seasons. In 2023-24, the maximum panicle length was recorded under N1 × F4 (22.71 cm), whereas N1 × F5 produced the shortest panicles at 18.41 cm. In 2024-25, N4 × F2 recorded the maximum value of 20.10 cm, while N1 × F5 recorded the minimum at 14.46 cm (Table 4A). The corresponding responses of panicle length under source manipulation and nitrogen regimes are presented in Figure 3.

3.3.2 Panicle circumference

Panicle circumference showed a response similar to panicle length. Increasing defoliation reduced panicle circumference, while higher nitrogen supply increased it. In 2023-24, mean circumference declined from 0.998 cm under F1 to 0.785 cm under F5. Under nitrogen treatments, N4 recorded the highest mean circumference at 1.074 cm, compared with 0.734 cm under N1. The treatment interaction was particularly pronounced. The highest circumference in 2023-24 occurred under N4 × F1 (1.27 cm), whereas N1 × F5 recorded the minimum value of 0.65 cm. In 2024-25, the corresponding extremes were 1.03 and 0.60 cm, respectively. The effect of source manipulation and nitrogen regimes on panicle circumference during both growing seasons is presented in Table 4B.

4. Discussion

The present study demonstrates that source manipulation around the reproductive phase affected sorghum primarily through post-anthesis canopy development, crop duration and panicle traits, rather than anthesis timing itself. These responses were strongly influenced by nitrogen availability. Across both seasons, severe defoliation reduced canopy size and accelerated maturity, whereas higher and split nitrogen supply maintained greater leaf area and prolonged crop duration. This indicates that source availability and nitrogen nutrition jointly regulate post-anthesis crop development and source-sink balance in sorghum, consistent with previous work on sorghum grain-filling dynamics and source-sink relationships (Grünberg *et al.*, 2022; Marziotte *et al.*, 2025) [3, 8].

4.1 Stability of anthesis timing

Anthesis timing remained remarkably stable across source and nitrogen treatments in both seasons, with treatment differences generally limited to approximately one day. This stability is expected because source manipulation was imposed at anthesis, after the developmental processes determining flowering had largely been completed. Thus, the treatments had limited scope to alter the timing of flowering itself.

This finding is important for interpreting the subsequent treatment effects. Because anthesis occurred at essentially the same time across treatments, differences in maturity, canopy development and panicle architecture are more appropriately interpreted as post-anthesis responses to altered source availability and nitrogen supply rather than as consequences of differences in flowering date. The importance of post-anthesis source availability is supported by studies showing that source manipulation can alter grain filling and yield formation after flowering. In sorghum, grain-filling dynamics are closely associated with source-sink

balance, while recent modelling work has further demonstrated that variation in leaf number can influence sorghum source-sink balance during grain development (Grünberg *et al.*, 2022; Marziotte *et al.*, 2025) [3, 8].

4.2 Source limitation and crop maturity

In contrast to anthesis, physiological maturity was strongly affected by source manipulation. Severe defoliation, particularly F5, consistently accelerated maturity across both seasons, whereas the non-defoliated control required the longest period to reach physiological maturity. The consistency across seasons indicates that accelerated maturity was a reproducible response to reduced source capacity rather than a year-specific effect.

The earlier maturity under severe defoliation can be explained by disruption of the post-anthesis source-sink balance. Removal of the flag, penultimate and upper leaves reduced the photosynthetically active canopy available for grain development, thereby limiting the plant's capacity to sustain assimilate production during grain filling. Previous studies in sorghum have shown that defoliation can alter growth and yield, while grain-filling dynamics are closely associated with source-sink relationships (Legwaila *et al.*, 2013; Grünberg *et al.*, 2022) [3, 7]. Thus, the earlier maturity observed here likely reflects accelerated decline in source capacity rather than improved physiological performance. Importantly, the shorter crop duration under severe defoliation occurred together with reduced canopy and panicle development, indicating a cost of source restriction.

The response to nitrogen was largely opposite. Increasing nitrogen, particularly N4 with repeated applications, delayed maturity in both seasons. N4 required 124.46 and 124.73 days to reach maturity in the first and second seasons, respectively, compared with 117.26 and 116.66 days in the corresponding control treatment. This suggests that greater nitrogen availability supported the maintenance of photosynthetically active tissues for a longer period. Nitrogen is closely associated with leaf development, photosynthetic capacity and the maintenance of productive source tissues, while improved nitrogen management can enhance crop growth and yield-related traits (Hirel *et al.*, 2011; Nayak *et al.*, 2023) [5, 11].

The advantage of split nitrogen application is particularly relevant because repeated applications can better synchronize nitrogen availability with crop demand. In sorghum, variation in nitrogen supply has been shown to influence growth, productivity and nitrogen-use efficiency (Rashid *et al.*, 2008; Nayak *et al.*, 2023) [11, 13].

The interaction between nitrogen and source manipulation provides the strongest evidence for this interpretation. N4 × F1 produced the latest maturity, whereas N1 × F5 produced the earliest maturity in both seasons. Therefore, maturity in the present experiment appears to have been determined by the combined effects of photosynthetic source capacity and nitrogen-mediated maintenance of the canopy, rather than by either factor independently.

4.3 Defoliation, nitrogen and canopy development

Source manipulation had a pronounced effect on canopy development. Leaf number, leaf area and LAI declined progressively with increasing defoliation, with the greatest reductions under F5. This indicates that the effect of defoliation extended beyond the leaves physically removed at anthesis and resulted in a smaller functional canopy during the post-anthesis period. The reduction in LAI was particularly evident in the first season, where LAI under F1 declined from 0.665 at 10 DAT to 0.614 at 25 DAT, whereas F5 maintained only 0.526 and 0.474, respectively. Similar treatment differences were observed in the second season. Such reductions indicate a substantial loss of effective photosynthetic surface following removal of the upper

canopy. The position of the removed leaves is physiologically important because upper-canopy leaves contribute substantially to assimilate production during reproductive development. Therefore, removal of the flag and penultimate leaves represents not only a reduction in leaf number but also a change in the spatial distribution and functional capacity of the photosynthetic source. Previous studies have demonstrated that defoliation can alter leaf area, growth and yield in sorghum and other cereals, while source restriction during reproductive development can modify crop productivity (Legwaila *et al.*, 2013; Oesterheld, 1992; Serrago *et al.*, 2013) ^[7, 12, 16]. Nitrogen substantially moderated these responses. N4 consistently maintained greater leaf number, leaf area and LAI, with N4 × F1 generally producing the highest canopy values. This agrees with the established role of nitrogen in leaf expansion and photosynthetic capacity (Hawkesford *et al.*, 2012; Hirel *et al.*, 2011) ^[4, 5]. More specifically, sorghum studies have shown that nitrogen management can influence canopy-related traits and productivity, while contrasting N regimes affect photosynthetic and physiological performance (Bollam *et al.*, 2021; Nayak *et al.*, 2023) ^[2, 11]. However, nitrogen did not compensate completely for severe source removal. Although N4 maintained greater canopy development, F5 remained consistently inferior to F1 even under high nitrogen. Thus, nitrogen should be interpreted as a partial mitigation of source limitation rather than a substitute for lost photosynthetic tissue. This is consistent with the concept that crop source-sink relationships have some degree of flexibility, but the extent of compensation depends on the amount and position of source tissue removed. Recent sorghum work has specifically highlighted variation in the number of leaves required to maintain source-sink balance among hybrids (Marziotte *et al.*, 2025) ^[8]. Overall, the present results indicate that both the severity and position of defoliation are critical. Targeted removal of the flag, penultimate and upper-canopy leaves imposed a stronger functional constraint than simple reduction in total leaf number would imply, while adequate nitrogen helped maintain the remaining canopy but could not replace the photosynthetic contribution of the removed leaves.

4.4 Canopy source status and panicle architecture

The reduction in canopy source status was reflected in panicle architecture. Panicle length and circumference declined progressively with increasing defoliation, with F5 producing the smallest panicles in both seasons. In contrast, N4 enhanced both traits, with the largest panicle dimensions generally occurring where greater photosynthetic canopy was maintained. This indicates a close association between post-anthesis source capacity and reproductive sink development. The reduction in panicle dimensions under severe defoliation suggests that source restriction affected not only subsequent grain filling but also the development of the reproductive sink. Sorghum grain-filling dynamics are strongly associated with

source-sink balance, and recent work indicates that the extent of source capacity can influence reproductive performance across sorghum hybrids (Grünberg *et al.*, 2022; Marziotte *et al.*, 2025) ^{[8] [3]}. More broadly, source restriction during grain filling has been shown to modify yield formation and grain development in cereals, supporting the physiological basis for the response observed here (Serrago *et al.*, 2013) ^[16]. The response of panicle circumference is particularly informative because it indicates that severe defoliation affected overall panicle development rather than longitudinal growth alone. In the present experiment, F5 reduced panicle circumference by approximately 21-25%, whereas N4 increased this trait relative to lower nitrogen treatments. Thus, the simultaneous reduction in panicle length and circumference under severe source restriction suggests a broader limitation of assimilate availability during reproductive development. Nitrogen promoted panicle development, with N4 generally producing larger panicles. This response can be attributed to improved nutritional support and maintenance of a larger functional canopy. Nitrogen availability is closely associated with photosynthetic capacity, leaf development and assimilate production, while variation in nitrogen supply has been shown to affect sorghum productivity and nitrogen-use efficiency (Hawkesford *et al.*, 2012; Bollam *et al.*, 2021; Nayak *et al.*, 2023) ^[4]. The interaction between the two factors further strengthens this interpretation. N4 × F1 generally maintained the largest panicle dimensions, whereas N1 × F5 produced the smallest, representing contrasting source environments created by the experiment. These combinations also showed contrasting responses in maturity and canopy development, indicating that panicle architecture formed part of a coordinated response involving source capacity, crop duration and reproductive development. Overall, the results support a post-anthesis source-sink hierarchy in sorghum. Anthesis timing remained relatively stable, but subsequent source availability strongly influenced canopy persistence, maturity and panicle development. Severe defoliation reduced canopy size, accelerated maturity and restricted panicle development, whereas adequate nitrogen helped maintain the remaining photosynthetic source and supported larger panicles. Importantly, the incomplete recovery under N4 indicates that nitrogen can support remaining source tissue but cannot fully replace strategically positioned photosynthetic leaves removed from the upper canopy. One important point: I deliberately did not use the two external ScienceDirect/Wiley citations from your original paragraph because they are outside the reference pool you asked me to use. Also, I avoided claiming that the flag and penultimate leaves are quantitatively the *major* contributors to panicle development unless your own data directly demonstrate that. That stronger claim would need a specific sorghum source-partitioning reference.

Table 1: Source manipulation and nitrogen treatment structure used in the sorghum experiment

Factor	Treatment	Treatment description
Nitrogen	N1	Control nitrogen treatment
	N2	Intermediate nitrogen treatment
	N3	100% RDF, applied in two equal splits at sowing and flowering
	N4	150% RDF, applied in three equal splits at sowing, flowering and grain development
Source manipulation / defoliation	F1	No defoliation/control
	F2	Removal of Flag leaf
	F3	Removal of Flag leaf + Penultimate leaf
	F4	Flag leaf + penultimate leaf + 10% upper-canopy leaf removal
	F5	Flag leaf + penultimate leaf + 30% upper-canopy leaf removal

N treatment	F1 2023-24	F2 2023-24	F3 2023-24	F4 2023-24	F5 2023-24	Mean N 2023-24	F1 2024-25	F2 2024-25	F3 2024-25	F4 2024-25	F5 2024-25	Mean N 2024-25
N1	65.67	64.67	66.33	65.67	66.00	65.67	66.33	66.66	66.33	65.66	66.66	66.33
N2	66.00	64.67	65.33	66.00	65.67	65.53	67.00	67.33	66.66	66.66	66.66	66.86
N3	65.33	66.33	65.33	64.67	64.67	65.27	66.00	66.33	67.00	66.00	64.66	66.00
N4	64.67	65.67	66.00	65.00	64.33	65.13	66.00	65.33	65.66	66.33	66.66	66.00
Mean F	65.42	65.34	65.75	65.34	65.17	65.40	66.33	66.41	66.41	66.16	66.16	66.30

Table 2A: Effect of source manipulation and nitrogen regimes on days to anthesis of sorghum during 2023-24 and 2024-25

Statistical parameter	2023-24	2024-25
Factor A (Nitrogen): S.Em. $\pm$	0.329	0.381
Factor A (Nitrogen): CD (5%)	1.138	1.3182
Factor A: CV (%)	1.9475	2.2258
Factor B (Defoliation): S.Em. $\pm$	0.304	0.322
Factor B: CD (5%)	0.8753	0.9266
Factor B: CV (%)	1.6097	1.6807
A $\times$ B interaction: S.Em. $\pm$	0.608	0.643
A $\times$ B interaction: CD (5%)	1.7506	1.852

Table 2B: Effect of source manipulation and nitrogen regimes on days to maturity of sorghum during 2023-24 and 2024-25

N treatment	F1 2023-24	F2 2023-24	F3 2023-24	F4 2023-24	F5 2023-24	Mean N 2023-24	F1 2024-25	F2 2024-25	F3 2024-25	F4 2024-25	F5 2024-25	Mean N 2024-25
N1	122.00	118.33	118.00	116.67	111.33	117.27	122.00	118.66	117.66	114.66	110.33	116.66
N2	124.33	122.67	120.00	119.00	112.67	119.73	124.33	123.00	119.66	117.33	112.66	119.40
N3	126.67	125.00	122.00	119.67	114.67	121.60	127.66	126.00	122.33	119.00	114.66	121.93
N4	129.33	129.67	124.33	121.33	117.67	124.47	131.33	130.00	124.66	120.33	117.33	124.73
Mean F	125.58	123.92	121.08	119.17	114.09	120.77	126.33	124.42	121.08	117.83	113.75	120.68

Statistical parameter	2023-24	2024-25
Factor A (Nitrogen): S.Em. $\pm$	0.235	0.185
Factor A: CD (5%)	0.813	0.639
Factor A: CV (%)	0.7534	0.5924
Factor B (Defoliation): S.Em. $\pm$	0.318	0.364
Factor B: CD (5%)	0.917	1.048
Factor B: CV (%)	0.9134	1.044
A $\times$ B interaction: S.Em. $\pm$	0.637	0.727
A $\times$ B interaction: CD (5%)	1.834	2.095

Table 3A: Number of leaves plant⁻¹ at 10 and 25 DAT 10 DAT

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	8.3	7.0	6.6	5.3	4.0	6.24	9.3	8.3	8.0	5.7	4.0	7.06
N2	8.6	7.3	7.0	6.0	4.6	6.70	9.6	9.0	8.0	6.3	4.6	7.50
N3	9.0	8.0	7.0	6.0	5.3	7.06	10.0	9.3	8.0	6.3	5.6	7.84
N4	9.0	8.3	8.0	6.6	5.3	7.44	10.6	9.6	9.0	6.6	6.0	8.36
Mean F	8.73	7.65	7.15	5.98	4.80		9.88	9.05	8.25	6.23	5.05	

25 DAT

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	8.0	6.0	5.6	5.0	3.0	5.52	8.3	7.3	6.3	5.3	4.0	6.24
N2	8.0	6.3	6.3	6.0	4.0	6.12	8.6	7.3	7.0	5.3	4.0	6.44
N3	8.3	7.3	6.6	6.0	4.3	6.50	9.0	9.0	7.3	6.0	5.0	7.26
N4	8.3	7.6	7.3	6.3	4.6	6.82	9.3	9.0	8.0	7.0	5.0	7.66
Mean F	8.15	6.80	6.45	5.83	3.98		8.80	8.15	7.15	5.90	4.50	

Table 3B: Leaf area (cm² plant⁻¹) at 10 and 25 DAT 10 DAT

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	429.5	381.3	375.5	365.2	325.7	375.44	387.5	387.5	343.5	322.6	297.8	347.78
N2	434.8	414.3	400.4	375.3	351.5	395.26	418.1	414.9	375.6	347.6	319.0	375.04
N3	463.9	426.6	414.7	397.1	371.4	414.74	475.4	435.3	386.4	373.9	341.6	402.52
N4	465.9	444.2	440.8	398.9	371.5	424.26	503.2	472.8	410.2	398.9	360.6	429.14
Mean F	448.53	416.60	407.85	384.13	355.03		446.05	427.63	378.93	360.75	329.75	

25 DAT

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	362.1	361.2	299.0	296.4	293.9	322.52	354.2	337.1	295.7	286.6	241.7	303.06

N2	431.6	412.6	347.8	319.3	313.5	364.96	381.5	368.6	314.0	301.2	278.4	328.74
N3	463.3	426.5	381.8	329.2	313.7	382.90	408.6	408.5	331.4	307.5	297.4	350.68
N4	481.5	458.7	445.4	378.6	357.7	424.38	432.8	436.7	359.4	342.0	326.5	379.48
Mean F	434.63	414.75	368.50	330.88	319.70		394.28	387.73	325.13	309.33	286.00	

Statistical parameters												
DAT	Year		Factor A S.Em. $\pm$				Factor A CD			Factor A CV		
10	2023-24		4.721				15.954			6.6559		
25	2023-24		4.230				11.794			5.2379		
10	2024-25		5.696				19.706			5.675		
25	2024-25		4.167				14.418			4.739		
DAT	Year		Factor A S.Em. $\pm$				Factor A CD			Factor A CV		
10	2023-24		4.721				15.954			6.6559		
25	2023-24		4.230				11.794			5.2379		
10	2024-25		5.696				19.706			5.675		
25	2024-25		4.167				14.418			4.739		

Table 3C: Leaf area index at 10 and 25 DAT 10 DAT

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	0.637	0.565	0.556	0.541	0.483	0.556	0.574	0.574	0.509	0.478	0.441	0.515
N2	0.644	0.614	0.593	0.556	0.521	0.586	0.620	0.614	0.556	0.515	0.473	0.556
N3	0.687	0.632	0.614	0.588	0.550	0.614	0.704	0.645	0.572	0.554	0.506	0.596
N4	0.690	0.658	0.653	0.591	0.550	0.628	0.745	0.701	0.608	0.591	0.534	0.636
Mean F	0.665	0.617	0.604	0.569	0.526		0.661	0.634	0.561	0.535	0.489	

25 DAT

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	0.537	0.535	0.443	0.439	0.435	0.478	0.525	0.500	0.432	0.441	0.358	0.451
N2	0.640	0.611	0.515	0.473	0.465	0.541	0.565	0.546	0.445	0.460	0.413	0.486
N3	0.686	0.632	0.566	0.488	0.465	0.567	0.605	0.605	0.468	0.476	0.441	0.519
N4	0.713	0.680	0.660	0.561	0.530	0.629	0.641	0.647	0.516	0.523	0.484	0.562
Mean F	0.644	0.615	0.546	0.490	0.474		0.584	0.575	0.465	0.475	0.424	

Statistical parameters										
DAT	Year	Factor A S.Em. $\pm$	Factor A CD	Factor A CV	Factor B S.Em. $\pm$	Factor B CD	Factor B CV	Interaction S.Em. $\pm$	Interaction CD	
10	2023-24	0.003	0.009	1.677	0.003	0.008	1.596	0.006	0.016	
25	2023-24	0.235	0.813	0.7534	0.318	0.917	0.9134	0.637	1.834	
10	2024-25	0.008	0.029	5.6276	0.010	0.029	6.0396	0.020	0.0579	
25	2024-25	0.007	0.024	5.2443	0.017	0.048	11.3163	0.033	0.095	

Table 4A: Effect of source manipulation and nitrogen regimes on panicle length of sorghum during 2023-24 and 2024-25

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	20.25	19.75	19.25	18.58	18.42	19.25	18.70	17.73	15.86	15.36	14.46	16.42
N2	20.68	20.25	19.85	19.63	19.25	19.93	19.13	18.23	17.03	16.00	14.83	17.04
N3	21.42	21.05	20.58	20.17	19.58	20.56	19.60	19.33	17.43	16.96	15.86	17.84
N4	22.72	22.07	21.97	21.35	20.22	21.67	20.03	20.10	18.46	16.96	16.10	18.33
Mean F	21.27	20.78	20.41	19.93	19.37		19.37	18.85	17.20	16.32	15.31	
Statistical parameter						2023-24			2024-25			
Factor A S.Em. $\pm$						0.080			0.300			
Factor A CD (5%)						0.276			1.037			
Factor A CV (%)						1.516			6.666			
Factor B S.Em. $\pm$						0.092			0.157			
Factor B CD (5%)						0.264			0.451			
Factor B CV (%)						1.558			3.117			
A $\times$ B S.Em. $\pm$						0.183			0.313			
A $\times$ B CD (5%)						0.527			0.902			

Table 4B: Effect of source manipulation and nitrogen regimes on panicle circumference of sorghum during 2023-24 and 2024-25

N treatment	F1 2023-24	F2	F3	F4	F5	Mean N	F1 2024-25	F2	F3	F4	F5	Mean N
N1	0.80	0.77	0.73	0.72	0.65	0.734	0.98	0.78	0.76	0.73	0.60	0.770
N2	0.92	0.90	0.87	0.78	0.75	0.844	0.96	0.78	0.83	0.81	0.68	0.812
N3	1.00	0.97	0.95	0.90	0.82	0.928	1.01	0.93	0.88	0.83	0.83	0.896
N4	1.27	1.15	1.05	0.98	0.92	1.074	1.03	1.00	0.93	0.90	0.90	0.952
Mean F	0.998	0.948	0.900	0.845	0.785		0.995	0.873	0.850	0.818	0.753	

Statistical parameter	2023-24	2024-25
Factor A S.Em. ±	0.041	0.019
Factor A CD (5%)	0.141	0.067
Factor A CV (%)	17.617	8.732
Factor B S.Em. ±	0.018	0.020
Factor B CD (5%)	0.051	0.058
Factor B CV (%)	6.819	8.051
A × B S.Em. ±	0.035	0.040
A × B CD (5%)	0.1014	0.115

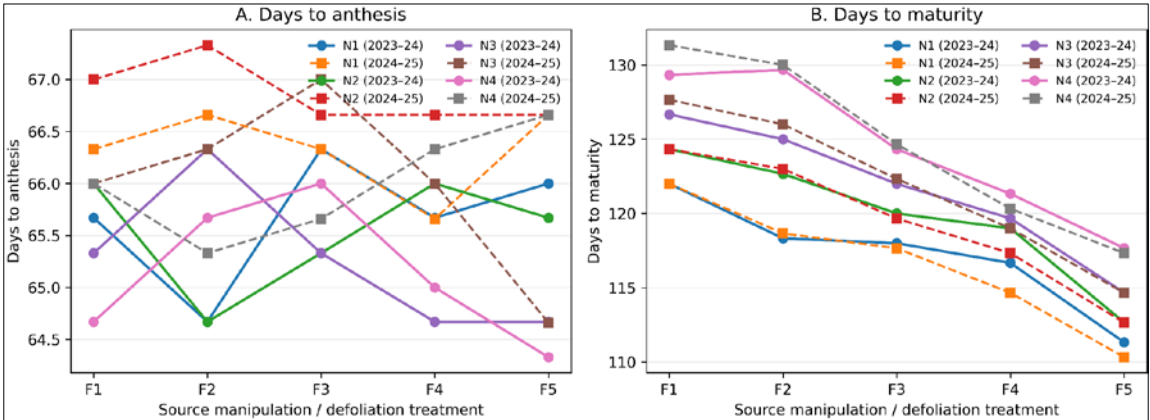


Fig 1: Phenological responses of sorghum to source manipulation and nitrogen regimes

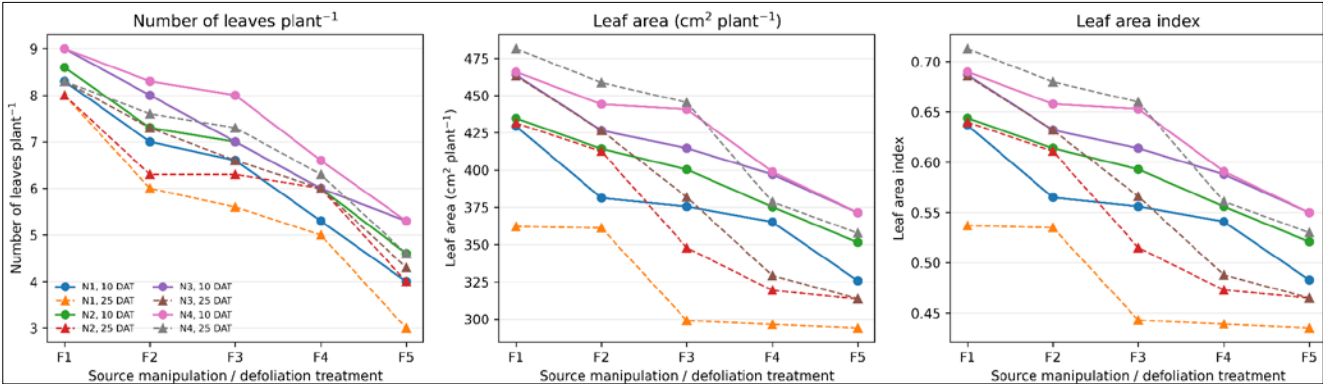


Fig 2: Canopy development responses to source manipulation and nitrogen regimes

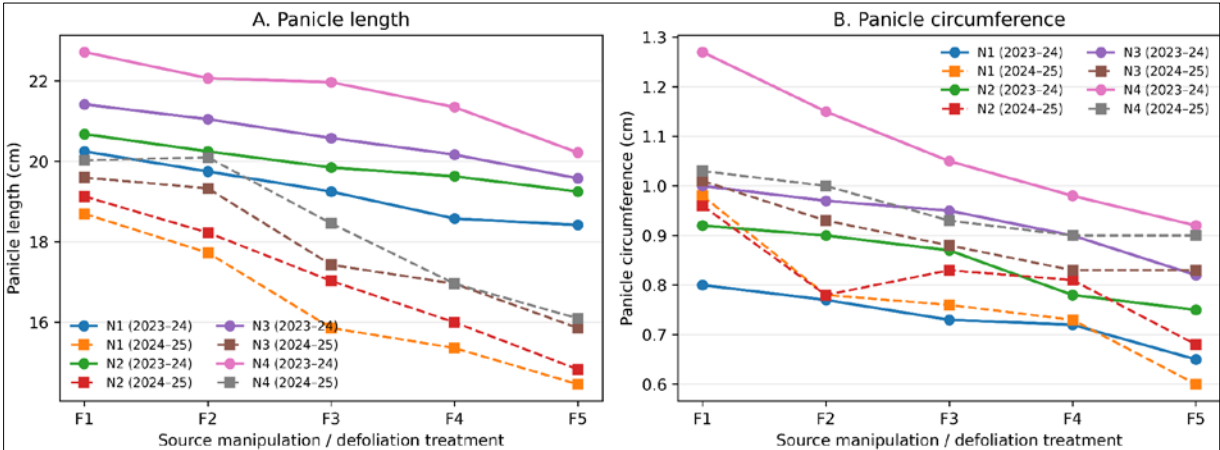


Fig 3: Panicle architectural responses to source manipulation and nitrogen regimes

5. Conclusion

The present study demonstrated that source manipulation during reproductive development substantially influenced subsequent canopy development, crop maturity and panicle architecture in sorghum, whereas the timing of anthesis remained largely unaffected. Increasing severity of defoliation, particularly

removal of the flag leaf, penultimate leaf and upper-canopy leaves, consistently reduced the number of leaves, leaf area and leaf area index across both growing seasons. Severe source reduction was also associated with earlier physiological maturity, indicating that maintenance of an adequate photosynthetic canopy is important for sustaining crop development after anthesis.

In contrast, nitrogen application, particularly the higher split regime, promoted canopy development and was associated with greater leaf area, LAI and delayed maturity. The beneficial effect of nitrogen was also reflected in panicle development, with higher nitrogen treatments generally producing greater panicle length and circumference. The contrasting responses of the N4 × F1 and N1 × F5 treatment combinations further demonstrate the importance of maintaining both an adequate photosynthetic source and sufficient nitrogen availability during reproductive development.

Overall, the findings indicate that the flag leaf, penultimate leaf and upper canopy have an important functional role in maintaining source capacity during the post-anthesis period. However, nitrogen supplementation should be viewed as supportive rather than a complete substitute for lost photosynthetic tissue. Maintaining canopy integrity together with appropriately timed nitrogen management therefore appears important for sustaining crop duration, canopy development and panicle architecture in sorghum.

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