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Defoliation of Autumn Planted Maize Hybrids for Sustainable Intensification of Maize-Soybean Intercropping System

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ABSTRACT

In maize-soybean intercropping systems (ICS), the morphophysiological growth traits and grain yield of component crops (CC), especially of soybean suffer greatly, owing to the dominance of maize in acquiring growth resources and shading effect. Thus, a field trial was conducted entailing maize hybrids (H_1= YH-1898 and H_2= YH-5427) and defoliation treatments (R_1= removal of top two leaves, R_2= removal of top four leaves, R_3= removal of top six leaves, and R_4= no removal of leaves) for boosting soybean (cv. AARI-soybean) growth and yield in maize-soybean ICS. The response variables included plant height (PH), 1000 grains weight, grain yield (GY), and biological yield (BY) along with the physiological growth traits (leaf area index LAI, leaf area duration LAD, crop growth rate CGR, and net assimilation rate NAR) of CC. The H_1 hybrid of maize outperformed the other hybrid by recording 8% and 9% higher PH and BY, respectively, while the H_2 hybrid depicted 18% and 6% greater 1000 grain weight and GY, respectively, along with NAR. Additionally, R_1H_2 exhibited the maximum LAI, LAD, and CGR at 30, 60, 90, and 110 days after sowing (DAS). Contrastingly, soybean recorded 11% higher PH in intercropping with the H_1 hybrid under R_4 defoliation treatment along with significantly higher 1000 grains weight (13%), GY (57%), BY (10%), and NAR (157%). Moreover, soybean exhibited the maximum physiological growth in response to the R_4H_1 treatment combination. On the basis of the recorded findings, the H_2R_1 treatment combination could be recommended for boosting maize yield, whereas H_1R_4 or H_1R_3 could be adopted to bolster the growth and productivity of soybean intercrop, but at the cost of a significant reduction in maize yield.

Keywords: biological nitrogen fixation, row intercropping, crop growth rate, leaf removal, net assimilation rate.

INTRODUCTION

Globally, maize (*Zea mays* L.) has been ranked as the third largest crop after wheat and rice (Islam et al., 2024), and it has become a strategic source of food, cooking oil, feed (dairy animals and poultry), and fuel production (Maqsood et al., 2020; Sedhom et al., 2024). Maize grain is composed of 68.5% carbohydrates, 8% lipids, 4% ash, 4% crude fiber, and 16.5% protein (Ullah et al., 2007; Iqbal et al., 2021a). It holds the potential to combat the malnutrition and food insecurity challenges presently confronted by South Asian and African countries (Ekpa et al., 2018; Khaliq et al., 2019). However, there exists a wide gap between maize production and requirements (Ali et al., 2016), despite significant genetic improvement of field crops using genetic engineering approaches (Li and Iqbal, 2024). Maize hybrids tend to perform differently in various environments (Ma et al., 2024); therefore, the selection of suitable genotypes in specific agro-environmental and soil conditions has become vital to improve productivity sustainably. Besides maize, soybean (*Glycine max.* (L.) Merrill), is the fourth largest cultivated crop and a key constituent of global food security worldwide (Elicin et al., 2021; Iqbal et al., 2022). It has become one of the main sources of plant protein and oil (Iqbal et al., 2021b; Eryiğit et al., 2022). Being a leguminous crop, it fixes atmospheric nitrogen (N) through biological N fixation via nodule formation which reduces the fertilizer requirement of the crop (Khan *et al.,* 2018). To increase the area under cultivation and yield of soybean, it is also planted in various intercropping systems (ICS) with maize, sorghum, sunflower, and fruit trees (Cui et al., 2024; Zhou et al., 2024). However, soybean tends to be exposed to shade conditions in ICS with cereals like maize (Echarte et al., 2011; Su et al., 2023), which necessitates conducting studies to bolster the productivity of component crops (CCs).

Intercropping systems (ICS) of maize with soybean hold the potential to impart sustainable intensification, alleviate competition between arable land and urbanization, along with increasing the production efficiency in rainfed and irrigated agro-ecosystems (Iqbal et al., 2018). ICS offer complementary advantages, because CCs vary in terms of nutrient demand and spatial distribution (Iqbal et al., 2019). Additionally, these promote the diversification of farm production and improve the sustainability of farmland ecosystems (Iqbal et al., 2017). Previously, the maize-soybean ICS has been reported to improve the fertility status and overall health of arable land along with alleviating environmental pollution and multiplying farmer's income (Abbas et al., 2021). Cultivable land has been persistently decreasing due to urbanization and industrialization, whereas maize-soybean intercropping can bridge the gaps between cooking oil production and demand (Sanginga, 2003). However, traditional cereal-legume ICS experienced yield losses of CC in comparison to their solo cultures (Banik et al., 2006; Deng et al., 2024), owing to a lack of synergistic temporal and spatial adjustments for growth resources. Moreover, broad leaves of soybean in ICS with narrow leaves crops like maize, sorghum, millets, etc. posed numerous challenges in terms of weed control and more importantly, the shading effect reduced the photosynthesis rate in soybean which pronouncedly reduced its growth and yield (Qu et al., 2022; Wang et al., 2022). Furthermore, defoliation constituted a stress type that significantly influenced morphophysiological traits, biochemical processes (Glier et al., 2015), and grain yield (Turek et al., 2023).

Previously, Ma et al. (2024) inferred that maize hybrids differed significantly in their potential, as ZF-2208 and DY-519 hybrids remained superior by recording 0.93–1.05 $t \cdot ha^{-1}$ grain production in China. Likewise, it was reported that YIGE1 caused variation in the genetic potential of maize hybrids by directly influencing the ear length and grain yield (Luo et al., 2022). However, Bonkoungou et al. (2024) concluded that few hybrids like TZEEIOR 509 × TZEEIOR 197 performed better than the rest of the hybrids under investigation and Li et al. (2023) attributed this variation to the superior adaptability of specific maize hybrids to moisture limited conditions. Moreover, it has been revealed that different maize hybrids performed differently in the field (Liu et al., 2022), owing to varying responses to growth factors (solar radiation, temperature, moisture, nutrients, etc.) (Kachapur et al., 2023; Matsuzaki et al., 2023; Adham et al., 2022), which led to significant variation in yield-contributing traits and grain yield (Mafouasson et al. 2018; Yousaf et al., 2021). Moreover, Yang et al. (2015) inferred that soybean yield in intercropping with maize tends to suffer owing to intense competition for growth resources, especially solar radiation and limited nutrients in the soil solution (Su et al., 2023). Furthermore, another study has reported that maize-soybean intercropping remained effective in boosting the biological characteristics of soil by contributing straw addition; however, soybean experienced higher yield losses owing to the dominance of the cereal CCs in acquiring the farm inputs (Cui et al., 2024; Zhou et al., 2024). However, these studies are limited in scope because different cultivars or hybrids of CCs respond differently to varying agroclimatic and soil conditions along with specific ICS, which makes it necessary to conduct site-specific field investigations.

Therefore, to bridge the research gaps, a research hypothesis was postulated that maize hybrids might perform differently in intercropping with soybean, and defoliation of maize hybrids could be effective in bolstering the productivity of component crops (maize and soybean) by virtue of more synergies in terms of utilization of growth resources. Thus, the prime aim of this trial was to sort out the superior maize hybrid for intercropping with soybean, whereas another aim was to assess the impact of defoliation of maize hybrids on morphophysiological and grain yield of component crops in the intercropping system.

MATERIALS AND METHODS

Experimental locality

The experiment was conducted at the Agronomic Research Area, Faculty of Agriculture, University of Agriculture Faisalabad, Faisalabad (Pakistan) (31.4504 N, 73.1350 E, and 186 m altitude) (Iqbal et al., 2024), during the autumn seasons of 2020–2021. The soil samples were taken from the experimental block from 0–30 cm depth by selecting the sampling sites of four corners and the middle of the experimental unit. The soil samples were collected using an auger and thereafter thoroughly mixed manually to make them homogenous and subsequently stored in zip lockable bags for conducting further analyses to determine the physico-chemical properties. The results revealed that the experimental soil was sandy clay loam with a pH of 8.1. It was low in organic matter (0.73%) and deficient in all macronutrients (nitrogen and phosphorous) except potassium. The soil of the experimental site was fine-textured with uniform soil particles.

Experimental treatments

The field experiment was comprised of maize leaf defoliation levels (R_1 = removal of top two leaves, R_2 = removal of top four leaves, R_3 = removal of top six leaves, and R_4 = no leaf removal) and two maize hybrids (H_1 = YH-1898 a semi-erect type hybrid, and H_2 = a spreading type hybrid YH-5427). The experiment was laid out in the factorial arrangement of the randomized complete block design (RCBD) using three replications. The net plot size of 7.5 × 8.0 m (10 rows per plot) was maintained for all experimental units in maize-soybean ICS.

Execution of the field trial

The experimental field was prepared by cultivating the soil thrice with a tractor-mounted cultivator followed by wooden planking with the aim of breaking apart the soil clods. The CCs (maize and soybean) were sown by following the recommended production technology package. The CCs were sown on ridges which were 75 cm apart in 2:2 ratios by using the manual dibbling method. The seed rate of 25 $kg \cdot ha^{-1}$ for maize hybrids (YH 1898 and YH 5427) and 75 $kg \cdot ha^{-1}$ for soybean (cv. AARI-soybean) was used. In maize-soybean ICS under investigation, nutrient requirements were fulfilled by supplying 250–125–125 $kg \cdot ha^{-1}$ NPK in the form of urea, diammonium phosphate (DAP), and sulfate of potash (SOP). No additional nutrients were applied to the soybean intercrop in all ICS. The P and K fertilizers were applied as basal dose, whereas N was supplied in three equal splits (basal dose, 35 days after sowing DAS, and 55 DAS). Irrigation scheduling was done according to the crop requirement and environmental conditions of the experimental locality. The first irrigation was applied at 8 DAS and subsequently, seven irrigations were applied at different stages until the CCs had attained physiological maturity. Appropriate plant protection measures were adopted to maintain the crop free of weeds, insects, and disease. To control the weeds, pre-emergence weedicides including Stomp (Pendimethalin) + Dual Gold (S-metolachlor) were applied, whereas acetochlor was sprayed as a post-emergence herbicide to keep weeds below threshold levels. Manual hoeing was also done twice (28 and 45 DAS) to control narrow and broadleaf weeds.

Recording of response variables

The response variables of CC included plant height (PH) which was measured by randomly selecting five plants from interior rows of each experimental unit and thereafter PH was determined using a tailor's measuring tape from the base of the plant to the tip of the highest leaf. Likewise, 1000 grains weight was measured by manually counting the grains and weighing them with the help of a digital balance. The grain yield (GY) was estimated by harvesting all plants of CC and their weight was determined separately. The biological yield was determined by adding GY to straw yield (SY) by following Equation 1 (Iqbal et al., 2016).

$$BY = GY + SY \quad (1)$$

Likewise, the leaf area index (LAI) of CC in maize-soybean ICS was estimated by using Equation 2.

$$LAI = \frac{Leaf\ area\ (\mathrm{m2})}{Ground\ area\ (\mathrm{m2})} \quad (2)$$

Moreover, crop growth rate (CGR), net assimilation rate (NAR), and leaf area duration (LAD) of CC in maize-soybean ICS were also recorded by following Equations 3, 4, and 5 respectively, as suggested by Iqbal et al. (2016).

$$LAD(\mathrm{days}) = \frac{(LAI1 + LAI2)\ (t2 - t1)}{2} \quad (3)$$

where: LAI_1 and LAI_2 are the leaf area indices of CC measured at times (days) t_1 and t_2, respectively.

$$CGR(g \cdot m^{-2} \cdot \text{day}^{-2}) = \frac{W2\,(\text{g}) - W1\,(\text{g})}{t2\,(\text{days}) - t1\,(\text{days})} \quad (4)$$

where: W_1 and W_2 represent plant weights of CC measured at times t_1 and t_2, respectively.

$$NAR(g \cdot m^{-2} \cdot \text{day}^{-1}) = \frac{TDM\,(t{\cdot}\text{ha}^{-1})}{LAD\,(\text{days})} \quad (5)$$

where: *TDM* represents total dry matter production of CC in maize-soybean ICS.

Statistical analyses

Data of response variables of both component crops were analyzed statistically by employing the two-way Fisher's analysis of variance (ANOVA) technique to determine the overall significance of employed treatments. Thereafter, the least significant difference (LSD) test at a 5% probability level was applied to compare the treatment means (Steel et al., 1997), using a computer-run statistical program (Statistix 8.1).

RESULTS

Maize plant height, 1000 grain weight, grain yield, biological yield, and net assimilation rate

The recorded data revealed that the interaction effect of maize defoliation and hybrids remained non-significant for response variables under investigation; however, their individual impact remained significant for all traits of maize except for the PH (Table 1). The recorded findings exhibited that the defoliation treatments remained ineffective as far as the PH of maize was concerned; however, the H_1 hybrid outperformed the other hybrid by recording 8% higher PH. Likewise, the defoliation treatment of R_1 (removal of top two leaves) remained superior by exhibiting the maximum 1000 grain weight and GY that were 9.5% and 10%, respectively, higher than the least performing defoliation treatment of R_4. In contradiction to PH, the H_2 hybrid remained superior by depicting 18% and 6% greater 1000 grain weight and GY, respectively, in maize-soybean ICS. In terms of BY, the R_1 defoliation treatment gave the maximum value (18.84 $t{\cdot}ha^{-1}$) and it was followed by the R_2 treatment. Moreover, contrary to 1000 grain weight and GY, the H_1 hybrid remained outmatched by recording 9% higher BY than the H_2 hybrid. The maximum NAR was exhibited by the H_1 hybrid, whereas R_1 and R_2 defoliation treatments remained statistically at par with each other, while the R_3 and R_4 treatments could not perform at par with the rest of the defoliation treatments (Table 1).

Maize leaf area index, leaf area duration, and crop growth rate

The interaction effects of maize defoliation treatments and hybrids had a significant influence on the physiological growth traits of maize (Table 2), except for the net assimilation rate (Table 1). According to the recorded findings, R_1H_2 (removal of top two leaves of the YH-5427 hybrid) remained unmatched by recording the maximum LAI at 30, 60, 90, and 110 DAS, whereas the highest values were noted at 60 DAS which kept on decreasing (at 90 and 110 DAS). This treatment combination was followed by R_1H_1 (removal of

Table 1. Plant height, 1000 grains weight, grain yield, biological yield, and net assimilation rate of the autumn planted maize as influenced by the defoliation of maize hybrids under irrigated semi-arid conditions of Faisalabad, Pakistan

Maize defoliation treatments	Plant height	1000-grains weight (g)	Grain yield ($t{\cdot}ha^{-1}$)	Biological yield ($t{\cdot}ha^{-1}$)	Net assimilation rate ($g{\cdot}m^{-2}{\cdot}day^{-1}$)
R_1 (removal of top two leaves)	209.40	357.50 A	7.77 A	18.84 A	8.21 A
R_2 (removal of top four leaves)	209.04	349.34 B	7.74 A	17.76 B	8.01 A
R_3 (removal of top six leaves)	210.08	340.33 C	7.30 B	17.19 C	7.81 B
R_4 (no removal of leaves)	209.60	326.67 D	7.03 C	16.04 D	7.10 C
LSD (≤ 0.05)	NS	6.42^{**}	3.35^{*}	0.46^{*}	0.28^{*}
Maize hybrids					
H_1 (YH-1898)	217.39 A	315.67 B	7.24 B	18.21 A	7.58 B
H_2 (YH-5427)	201.67 B	371.25 A	7.64 A	16.71 B	8.06 A
LSD (≤ 0.05)	15.02^{**}	60.62^{**}	0.43^{*}	1.72^{*}	0.64^{*}

Note: Numerical values having atypical letters indicate significant difference at probability level of 5% as per LSD test, whereas NS indicates statistical non-significant effects of employed treatments.

Table 2. Leaf area index, leaf area duration, and crop growth rate of the autumn planted maize as influenced by the defoliation of maize hybrids under irrigated semi-arid conditions of Faisalabad, Pakistan

Maize	Leaf area index				Leaf area duration (days)			Crop growth rate ($g \cdot m^{-2} \cdot day^{-1}$)		
DAS	30	60	90	110	60	90	110	60	90	110
R_1H_1	1.07b	4.08b	3.18b	1.97a	77.25b	186.15b	237.45b	16.12ab	18.99b	8.60b
R_1H_2	1.33a	4.23a	3.27a	1.98a	82.95a	195.45a	247.95a	16.22a	19.35a	8.76a
R_2H_1	1.03b	4.01c	3.13c	1.90b	76.60b	182.70c	233.10c	15.75b	18.55c	8.41c
R_2H_2	0.93c	4.00c	3.21ab	1.82c	73.95c	182.11c	232.72c	15.52c	18.18d	8.28d
R_3H_1	0.94c	3.97c	3.04d	1.83c	73.65c	176.68d	227.25d	15.30d	18.02e	8.26d
R_3H_2	0.88d	3.91d	3.07d	1.89b	70.85d	176.55d	226.15d	15.22e	17.30f	8.12e
R_4H_1	0.91cd	3.44d	2.21e	1.79c	69.25d	173.25e	231.75c	14.85f	17.29f	7.91f
R_4H_2	0.70e	3.30d	2.19e	1.51d	66.45e	165.75f	211.95e	14.62g	17.26f	7.89f

Note: Numerical values having atypical letters indicate significant difference at probability level of 5% as per LSD test. R_1 = removal of top two leaves, R_2 = removal of top four leaves, R_3 = removal of top six leaves, R_4 = no removal of leaves, H_1 = YH-1898, and H_2 = YH-5427.

top two leaves of the YH-1898 hybrid), while these treatments remained statistically at par with each other for LAI of maize recorded at 110 DAS. Overall, the treatment combination of R_4H_2 (no removal of leaves of the YH-5427 hybrid) could not perform at par with the rest of the treatments by exhibiting the minimum LAI at 30, 60, 90, and 110 DAS. As far as LAD and CGR of maize hybrids subjected to different defoliation treatments were concerned, R_1H_2 (removal of top two leaves of the YH-5427 hybrid) remained superior by exhibiting the maximum values, while it was followed by R_1H_2 (removal of top two leaves of YH-5427 hybrid) (Table 3). For these physiological growth traits of maize, the treatment combinations of R_4H_1 and R_4H_2 performed below par with the rest of the treatment combinations (Table 2).

Soybean plant height, 1000 grain weight, grain yield, biological yield, and net assimilation rate

According to the recorded data, the interaction effect of maize defoliation and hybrids remained non-significant for response variables of intercropped soybean; however, their individual impact remained significant for all traits except the PH (Table 3). It was noted that soybean recorded 11% higher PH when it was intercropped with the H_1 hybrid compared to another hybrid of maize under investigation. Interestingly, R_4 defoliation treatment surpassed the rest of the treatments by recording significantly higher 1000 grains weight (13%), GY (57%), BY (10%), and NAR (157%) of soybean in comparison to the least performing R_1 defoliation treatment. However, it was statistically at par with the R_3 defoliation treatment for these response variables of soybean intercropped with maize hybrids. Regarding soybean performance in intercropping with maize hybrids, it was revealed that soybean recorded significantly higher 1000 grains weight, GY, BY, and NAR when it was intercropped with (Table 3).

Soybean leaf area index, leaf area duration, and crop growth rate

The interaction effects of maize defoliation treatments and hybrids had a significant influence on the physiological growth traits of soybean (Table 4), except for the net assimilation rate (Table 3). The recorded findings revealed that soybean exhibited the maximum LAI at 30, 60, 90, and 110 DAS when it was intercropped with the YH-1898 maize hybrid that was not subjected to defoliation treatment (R_4H_1). It was followed by R_4H_2 (the YH-5427 maize hybrid without defoliation), whereas soybean intercropped with R_1H_1 (removal of top two leaves of the YH-1898 hybrid) exhibited the minimum LAI at 30, 60, 90, and 110 DAS. In terms of LAD and CGR of soybean intercropped with maize hybrids under irrigated conditions, the results depicted that R_4H_1 surpassed the rest of the treatment combinations by recording the highest values, while all treatments remained statistically non-significant for CGR of soybean recorded at 60 and 110 DAS. Overall, R_1H_1 gave the minimum CGR at 90 DAS along with LAI and LAD at 30, 60, 90, and 110 DAS (Table 4).

Table 3. Plant height, 1000 grains weight, grain yield, biological yield, and net assimilation rate of autumn planted soybean as influenced by the defoliation of maize hybrids under irrigated semi-arid conditions of Faisalabad, Pakistan

Maize defoliation treatments	Plant height (cm)	1000 grains weight (g)	Grain yield ($t \cdot ha^{-1}$)	Biological yield ($t \cdot ha^{-1}$)	Net assimilation rate ($g \cdot m^{-2} \cdot day^{-1}$)
R_1 (removal of top two leaves)	41.50	121.33 B	0.63 B	1.99 B	0.07 C
R_2 (removal of top four leaves)	40.61	123.50 B	0.73 B	2.03 B	0.08 BC
R_3 (removal of top six leaves)	43.56	132.00 A	0.91 A	2.07 AB	0.12 AB
R_4 (no removal of leaves)	44.31	137.00 A	0.99 A	2.19 A	0.18 A
LSD (≤ 0.05)	1.36^{NS}	6.98^{**}	8.85^{**}	3.49^{*}	5.52^{*}
Maize hybrids					
H_1 (YH-1898)	44.65 A	131.50 A	0.89 A	2.18 A	0.09 A
H_2 (YH-5427)	40.34 B	125.42 B	0.74 B	1.96 B	0.08 B
LSD (≤ 0.05)	4.49^{*}	5.82^{*}	6.63^{*}	22.35^{**}	5.43^{*}

Note: Numerical values having atypical letters indicate significant difference at probability level of 5% as per LSD (least significant difference) test, whereas NS indicates statistical non-significant effects of employed treatments.

Table 4. Leaf area index, leaf area duration, and crop growth rate of the autumn planted soybean as influenced by the defoliation of maize hybrids under irrigated semi-arid conditions of Faisalabad, Pakistan

Maize	Leaf area index				Leaf area duration (days)			Crop growth rate ($g \cdot m^{-2} \cdot day^{-1}$)		
DAS	30	60	90	110	60	90	110	60	90	110
R_1H_1	0.75f	2.17d	3.23f	1.53f	43.8f	124.8e	172.4e	0.18	0.15d	0.70
R_1H_2	0.55g	1.90e	3.30e	1.10g	32.25g	111.75f	133.75f	0.17	0.11e	0.70
R_2H_1	1.20c	2.27bc	3.29e	1.98e	52.05c	136.45c	193.15d	0.18	0.18c	0.70
R_2H_2	1.17c	2.30b	3.41d	2.29d	52.05c	137.7c	194.70d	0.18	0.18c	0.80
R_3H_1	0.95d	2.31b	3.60c	2.78c	49.50d	138.75c	202.55c	0.18	0.19c	0.70
R_3H_2	0.81e	2.23c	3.37d	2.80c	45.45e	129.45d	193.15d	0.18	0.19c	0.80
R_4H_1	1.35a	2.40a	4.19a	3.03a	56.25a	153.75a	225.05a	0.19	0.25a	0.90
R_4H_2	1.26b	2.39a	3.83b	2.89b	55.12b	148.35b	215.65b	0.18	0.21b	0.90

Note: Numerical values having atypical letters indicate significant difference at probability level of 5% as per LSD (least significant difference) test. R_1 = removal of top two leaves, R_2 = removal of top four leaves, R_3 = removal of top six leaves, R_4 = no removal of leaves, H_1 = YH-1898, and H_2 = YH-5427.

DISCUSSION

The recorded findings remained in concurrence with the research hypothesis, because maize hybrids performed differently when subjected to different defoliation treatments, while soybean intercropped with maize also recorded variations in the physiological growth traits and grain yield. The H_1 hybrid (YH-1898) recorded significantly higher plant height and biological yield; however, the H_2 hybrid (YH-5427) remained superior by depicting 18% and 6% greater 1000 grain weight and GY respectively, especially when its top two leaves were removed. The agro-climatic conditions and genetic makeup could be attributed to the variations in the PH of maize hybrids. Likewise, taller plants of semi-erect type maize hybrid contributed towards higher BY of maize grown in intercropping with soybean. Moreover, higher genetic potential and synthesis of greater assimilates by the H_2 hybrid under top two leaves removal as indicated by significantly higher NAR could be the reasons behind higher 1000 grains weight and GY. These results were in line with the findings of De Pelegrin et al. (2016), Ahmad et al. (2015), Afzal et al. (2015), and Layek et al. (2011), who concluded that phonological parameters like plant height and BY of different cultivars of maize varied significantly in organic farming systems due to differences in their genetic makeup. Leaves are considered to be a primary source of assimilates for grain yield due to their involvement in the biosynthesis of assimilates and their partitioning towards the sinks of crop plants. On the other hand, six leaves removal could have suppressed the biosynthesis and translocation of assimilates towards grain, and ultimately 1000 grains weight and GY were significantly reduced.

It was also concluded that defoliation treatments had a significant impact on seed weight and seed numbers per plant of maize (Raza et al., 2019a). Similarly, yield attributes like 1000 grain weight and robust physiological growth as indicated by NAR contributed strategically to the improvement of the GY of maize (Zamir et al., 2010). Moreover, maize hybrids differed significantly in their potential because the ZF-2208 and DY-519 hybrids surpassed the rest of the hybrids under investigation by recording 0.93–1.05 t ha^{-1} grain production (Ma et al., 2024). Furthermore, defoliation treatments influenced the vegetative and reproductive growth traits of maize except for kernel rows per cob (Ranković et al., 2021).

Moreover, R_1H_2 (R1H2 (removal of top two leaves of YH-5427 hybrid) recorded the maximum LAI, LAD, and CGR at 30, 60, 90, and 110 DAS, whereas the highest values were noted at 60 DAS which kept on decreasing onward (at 90 and 110 DAS). The significantly higher genetic potential of the YH-5427 hybrid and higher biosynthesis of assimilates triggered by defoliation of the top two leaves might be credited for triggering the physiological growth of maize. Previously, Raza et al. (2019b) also stated that maize leaf removal bolstered the LAI of CC in maize-soybean ICS. It was also inferred that LAD reflected the duration of active photosynthesis time of maize that greatly influenced the CGR. Significantly higher CGR was ascribed to improved LAI and LAD in different types of cereal-legume ICS (Andrade, 1995; Raza et al., 2019c). Severe defoliation drastically reduced transpiration rate and photosynthesis, however, a moderate reduction in leaf area enabled soybean plants to continue photosynthesis to ensure optimum grain production (Turek et al., 2023). Moreover, optimum and judicial defoliation resulted in improved growth of maize (Raza et al., 2019a). However, suboptimal leaf defoliation resulted in slower seed maturation and also caused a serious reduction in physiological growth traits of maize inbred lines (Ranković et al., 2021). Similar to the obtained findings, Heidari (2015) also inferred that defoliation and ½ ear removal treatments significantly influenced the growth traits of maize.

In contradiction to maize, the intercropped soybean recorded the maximum PH, 1000 grain weight, GY, BY, and NAR when it was intercropped with the H_1 hybrid of maize subjected to the R_4 defoliation treatment. These variations could be due to different canopy diameters of maize hybrids and each hybrid was of different leaf angles that significantly influenced soybean yield attributes and GY. Moreover, Fan et al. (2018) also concluded that being a light-loving plant, soybean performed comparatively better when exposed to higher solar radiation, especially photosynthetically active radiation (PAR), and therefore, defoliation of six leaves of maize probably improved the penetration of PAR to soybean in ICS. Moreover, the reduction of shade effects might also be ascribed to higher NAR, owing to improved photosynthesis (Iqbal et al., 2016) which ultimately led to higher GY and BY of soybean intercropped with maize.

Following the trend, soybean intercropping with the H_1 maize hybrid subjected to the removal of six leaves (R_4) remained effective in boosting the LAI, LAD, and CGR of soybean. Significantly greater LAI and LAD presented higher leaf area and the time period of active photosynthesis, respectively, which led to improved performance of CC in ICS (Iqbal et al., 2017). It might be inferred that the removal of six leaves of maize improved the penetration of PAR to the comparatively dwarf soybean plants and ultimately physiological growth was increased (Raza et al., 2019b). Similarly, soybean physiological growth traits and yield were significantly improved when it was intercropped with cereals in wider row spacing which allowed sufficient penetration of PAR to dwarf soybean plants (Iqbal et al., 2018). Moreover, soybean seed yield was linearly driven with increments in light interception which triggered energy conversion and boosted the partitioning efficiencies (Koester et al., 2014).

CONCLUSIONS

The recorded findings were in concurrence with the research hypothesis, as maize hybrids responded differently to defoliation treatments, while soybean intercropped with maize also recorded variations in the physiological growth traits and grain yield. The H_1 hybrid (YH-1898) recorded significantly higher plant height and biological yield, however, the H_2 hybrid (YH-5427) subjected to defoliation treatment involving removal of top two leaves (R_1) remained superior by depicting significantly higher 1000 grain weight and GY. The same treatment combination (H_2R_1) outperformed the rest of the treatment combinations by recording the maximum physiological growth traits, such as leaf area index and duration along with the crop growth rate of maize. Thus, H_2R_1 could be recommended to bolster the growth and grain yield of maize in intercropping with soybean. In contradiction, soybean intercropped with maize performed better with the H_1 hybrid subjected to the severe defoliation treatment (R_4 = removal of six leaves of maize). On the basis of the recorded findings, it might be inferred that H_1R_4 or H_1R_3 could be adopted to bolster the growth and productivity of soybean intercrop, but at the cost of a reduction in maize yield. Therefore, the selection of suitable maize hybrids and judicious defoliation of maize leaves could be developed as a potent strategy to bolster the productivity of CC in maize-soybean ICS. However, future research must focus on investigating the impact of severe defoliation such as the removal of eight leaves of maize, and adjusting the spatial arrangement of maize-soybean intercrops. Such optimization holds the potential to reduce the competition for growth resources among CC and promote spatio-temporal complementary association among intercrops similar to their solo cultures.

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