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Investigating the Impact of Intercropping Time of Soybean (*Glycine max*) and Haricot Bean (*Phaseolus vulgaris* L.) With Sorghum on Striga (*Striga hermonthica*) Control and Crop Productivity in Kobo, North Wollo Zone, Ethiopia

Mohammed Hussen[1] | Zeru Asefa[1] | Alemu Molla[1] | Endalkachew Fekadu[2] | Moges Tadesse[2]

[1]Department of Plant Science, Woldia University, Woldia, Ethiopia | [2]Department of Soil Resource and Watershed Management, Woldia University, Woldia, Ethiopia

Correspondence: Mohammed Hussen (hussen2007mohammed@gmail.com)

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ABSTRACT

Striga weed infestation severely limits sorghum productivity in Ethiopia, particularly in North Wollo. A field experiment at the Sirinka Agricultural Research Center during the main cropping season evaluated the effects of intercropping sorghum with soybean and haricot bean at three legume sowing times: 2 weeks before, 1 week before, and simultaneous with sorghum planting. The experiment, laid out in a randomized complete block design with three replications, used the local sorghum variety "Jigurity," soybean "Wollo," and haricot bean "Lehode." Data on growth, yield, and Striga infestation were analyzed, alongside land equivalent ratio (LER) and monetary advantage index to assess biological and economic benefits. Results showed that haricot bean significantly reduced Striga counts more than soybean. The highest sorghum grain yields (2405.4 kg/ha) and LER (1.45) were achieved when legumes were planted two weeks before sorghum, with soybean intercropping yielding the greatest economic return (monetary advantage index = 21,804). Sorghum phenology, including days to 50% flowering and days to physiological maturity, was not significantly affected by the treatments, but plant height, grain yield, and biomass were significantly influenced by legume type and sowing time. In conclusion, intercropping sorghum with soybean or haricot bean, especially when legumes are sown 2 weeks prior to sorghum, can enhance yield and control Striga in North Wollo and similar areas. However, results should be validated through multiseason trials before broad recommendations.

1 | Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is one of the most important cereal crops worldwide and belongs to the family Poaceae. It is predominantly a self-pollinated crop, although natural cross-pollination may occur depending on panicle structure and environmental conditions [1]. Sorghum is a C4 photosynthetic plant characterized by high photosynthetic efficiency and superior water-use efficiency compared with many other cereal crops, enabling it to thrive under high temperature and drought conditions [2]. Because of these physiological characteristics, sorghum is well adapted to semiarid and drought-prone environments and can be cultivated successfully in areas receiving relatively low rainfall, making it an important crop for food security in arid and semiarid regions [3].

Global sorghum production exceeds 55 million metric tons annually, with major producing countries including the

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United States, Nigeria, Sudan, India, China, and Ethiopia. Sorghum is one of the most important cereal crops in the semiarid tropics and plays a critical role in food security for millions of smallholder farmers in sub-Saharan Africa due to its adaptability to drought-prone environments [4]. Ethiopia is among the leading sorghum producers in Africa, and the crop is widely cultivated in moisture-limited areas due to its tolerance to drought and high-temperature stress [5]. In northern Ethiopia and other moisture-limited regions of the country, sorghum remains a key cereal crop for rural households, contributing significantly to both food security and income generation, especially under drought-prone conditions where few other crops perform well [6].

A major biotic constraint to sorghum production in Ethiopia and across sub-Saharan Africa is the parasitic weed *Striga hermonthica* (Del.) Benth., which severely reduces cereal yields where it occurs [7]. Under heavy infestation, *S. hermonthica* can cause yield losses of up to 90% in sorghum and related cereals, depending on infestation level and host susceptibility [7]. The parasite's prolific seed production (tens to hundreds of thousands per plant) and long-lived seedbank make management difficult, and traditional farmer practices such as hand-weeding and simple crop rotation have generally failed to significantly reduce the seedbank or prevent reinfestation [8]. Although *Striga* is primarily known to attack sorghum, maize, and pearl millet, evidence suggests it can infest other cereals under conducive conditions, contributing to reduced productivity and threatening smallholder livelihoods [9].

Cereal–legume intercropping has been widely adopted in sub-Saharan Africa as a strategy to maximize land use, improve food security, and enhance soil fertility, and studies have shown that intercropping cereals such as sorghum with legumes like cowpea, green gram, or crotalaria can suppress *Striga hermonthica* infestations and improve crop productivity by reducing *Striga* emergence and promoting land equivalent ratios (LERs) greater than sole cropping [10].

Although intercropping of sorghum and legumes is a common practice in Ethiopia, little research has focused on optimizing the timing of legume introduction to maximize both Striga control and crop productivity. In the Kobo district, where Striga infestation is particularly severe, identifying the best time to intercrop soybean and haricot bean with sorghum is crucial for improving yields and ensuring sustainable production. This study, therefore, investigates the effect of intercropping time of soybean and haricot bean with sorghum on Striga suppression and crop productivity in Kobo, North Wollo Zone, Ethiopia.

2 | Materials and Methods

2.1 | Description of the Study Area

The study was conducted at the Kobo Subcenter of the Sirinka Agricultural Research Center, which is located in Kobo District of North Wollo Zone, Amhara National Regional State (Figure 1). The main town of the district is also called Kobo, which is found 415 km away from the eastern part of Bahir Dar and 570 km from northern Addis Ababa. Geographically, it is 12^0 08′ 21″N latitude and $39^0$35′21″ E longitude and at an altitude of 1450 m above sea level. It is a medium rainfall area, and very suitable for agricultural production with rainfall of 692.8 mm on average, and a minimum temperature of 22 degrees centigrade and maximum temperature of 30 degrees centigrade on average.

The experimental soil is a Vertisol, characterized by high clay content and distinct shrink-swell properties that result in deep cracks during dry periods. It is usually developed in medium rainfall areas and is highly suitable for agricultural production.

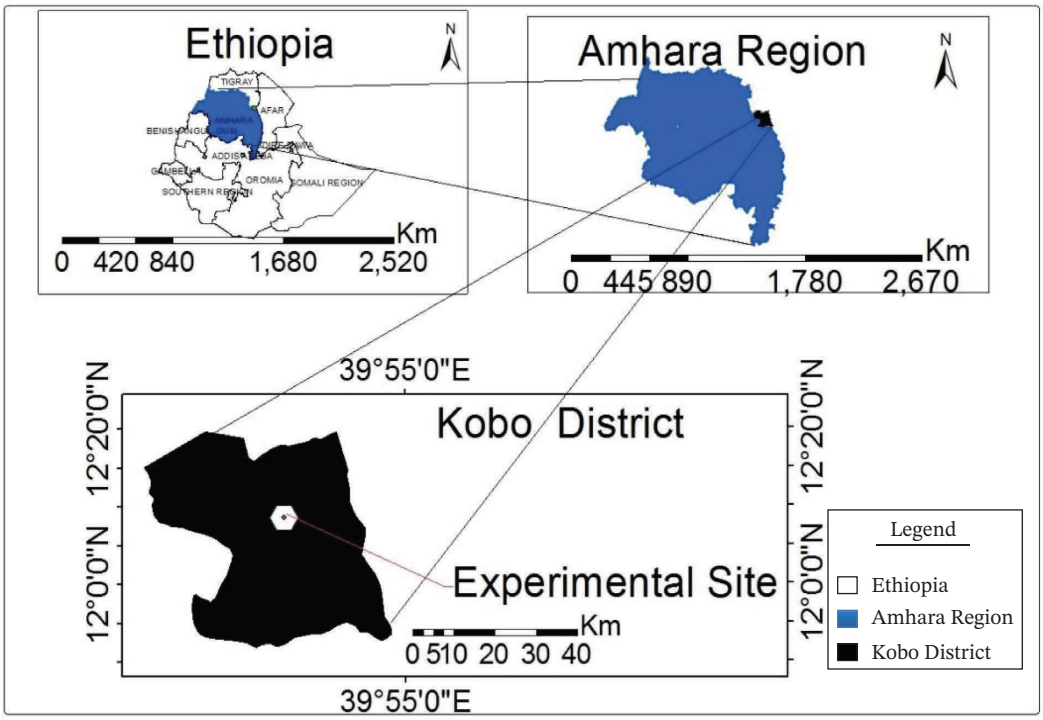


FIGURE 1 | Map of the study area. Source: map prepared by authors.

The laboratory analysis resulted in the topsoil of the study area having a 1.1% level of total nitrogen and 1.58% organic matter content. The pH (H_2O) of the soil was 7.5, and this falls within the slightly alkaline range, which is suitable for sorghum, as productive soils for the crop typically range from 5.5 to 8.5. Soil textural analysis results indicated that the texture of the experimental site was clay loam (Table 1).

2.2 | Planting Materials

A Striga-susceptible local sorghum variety (Jigurity), the "Wolo" variety of soybean, and "Lehode" variety of haricot bean, released by the Sirinka Agricultural Research Center, were used as experimental planting materials, and those seeds were taken from the Sirinka Agricultural Research Center.

2.3 | Treatments, Experimental Design, and Procedure

tFactorial combinations of two legume crops (soybean and haricot bean) and three intercropping times (legumes planted 2 weeks before sorghum, 1 week before sorghum, and on the same day as sorghum) along with their sole cropping treatments were arranged in a randomized complete block design (RCBD) with three replications (Table 2). The experiment was conducted on a Striga hotspot field with a history of natural infestation for several years. The gross size of each experimental plot was 3.75×3 m ($11.25\ m^2$). The net harvestable area for intercrop plots was 2.25×2.70 m ($6.08\ m^2$), consisting of the central three sorghum rows and the associated legume rows. The net plot and harvestable area for sole soybean and haricot bean were 2.8×2.8 m ($7.84\ m^2$).

To avoid border effects, the two outermost rows of soybean and haricot bean, and a 0.20 m row length at both ends of each plot, were treated as border areas and were excluded from all yield and yield-component measurements. Border rows were planted and managed the same as the inner rows, but were not harvested for data collection. The path widths were 1 m between plots and 1.5 m between blocks.

The land was plowed and harrowed using a tractor before being divided into replications and plots according to the experimental design and treatment layout. Planting rows were oriented along the longer side of each plot to maximize the number of crop rows per plot. In both intercropping and sole cropping, sorghum was planted at 75×15 cm spacing. In sole cropping, soybean and haricot bean were planted at 40×10 cm spacing on the same planting date as sorghum. However, in the intercropping treatments, legumes were planted between the two adjacent sorghum rows at 10-cm intrarow spacing according to the assigned planting-time treatments. Weeding and other cultural practices were carried out uniformly for all plots following recommended agronomic practices.

TABLE 1 | Soil physical and chemical properties of the experimental field before planting.

Soil properties	Values
Textural class	Clay
Sand (%)	23
Silt (%)	36
Clay (%)	41
Bulk density (gm/cm^3)	0.99
Particle density (gm/cm^3)	2.23
Porosity (%)	51
pH, H_2O (1: 2.5)	7.5
Organic matter (%)	1.56
Total nitrogen (%)	1.1

2.4 | Data Collection

Data on Striga count, phenology, growth, and yield-related parameters of the component crops were collected from the net plot areas at appropriate crop growth stages. Grain and other agronomic data of sorghum were collected from the central rows, excluding border rows on both sides, to avoid edge effects.

2.4.1 | Striga Count Parameter

- Striga counts m^{-2}: Striga counts m^{-2} were recorded using fixed quadrats (1×1 m) placed at two representative locations within each net plot at the sorghum flowering stage and again at physiological maturity and averaged. This approach was used to minimize variability and improve the reliability of Striga density estimates.

2.4.2 | Sorghum Parameters

2.4.2.1 | Phenological Parameters

- Days to 50% emergence: Defined as the number of days from sowing to the date when 50% of seedlings in the net plot had fully emerged above the soil surface (visible coleoptile exposure), assessed by direct plant counts, not visual estimation alone.
- Days to 50% heading: Defined as the number of days from sowing to the stage when 50% of plants in the net plot had fully exerted the panicle from the flag leaf sheath (panicle emergence), based on standard sorghum growth stage criteria.
- Days to physiological maturity: Defined as the number of days from sowing to the stage when approximately 90%–95% of panicles in the net plot reached physiological maturity, indicated by formation of a black layer at the base of the grain and hard kernel development, not based on leaf senescence or threshing ease.

2.4.2.2 | Vegetative Growth Parameters

- Plant height (cm): Measured at physiological maturity from ground level to the tip of the panicle (excluding awns) from 10 randomly selected plants per plot, and the average value was used.
- Panicle length (cm): Measured from the panicle base node (first panicle branch) to the tip of the panicle from 10 randomly selected plants per plot and averaged.

2.4.2.3 | Yield and Yield Components of Sorghum

- Head weight per plant (g): Measured from ten pretagged representative plants per plot. Heads were harvested, dried

TABLE 2 | Experimental treatment combinations and sole crops used for the study.

Types of legumes	Before 2 weeks of sorghum sowing (R2)	Time of sowing before 1 week of sorghum sowing (R1)	On the same day of sorghum sowing (R0)
Soybean (S)	SR2 (T1)	SR1(T2)	SR0 (T3)
Haricot bean (H)	HR2 (T4)	R1(T5)	HR0(T6)
Sole crop			
Sole soybean (T7)			
Sole haricot bean (T8)			
Sole sorghum (T9)			

to constant moisture, and weighed using a sensitive balance. The average was recorded.

- Thousand kernel weight (g): Determined using a standard subsampling procedure. Grain samples were thoroughly mixed, a random subsample was taken, and grains were counted using a seed counter and weighed. The weight was then converted to 1000-kernel weight and adjusted to 12.5% moisture content. Direct counting of 1000 grains from the total bulk was not used.
- Aboveground dry biomass: All aboveground plant parts from the net plot were harvested and oven-dried at 70°C until constant weight was achieved before biomass measurement to ensure standardized moisture conditions.
- Straw yield (kg ha^{-1}): Calculated as the difference between total aboveground dry biomass and grain yield on a dry weight basis.
- Grain yield (kg ha^{-1}): Grain yield was determined from the net plot area and adjusted to 12.5% standard grain moisture content using a moisture correction formula.
- Harvest index (HI) (%): HI was calculated as the ratio of grain yield to total aboveground dry biomass × 100.

2.4.3 | Legume Parameters

2.4.3.1 | Phenological Parameters

- Days to 50% emergence: Defined as days from sowing until 50% of seedlings in the net plot fully emerged above the soil surface, based on plant counts.
- Days to 50% flowering: Defined as days from sowing until 50% of plants in the net plot had at least one fully opened flower, without head formation.
- Days to physiological maturity: Defined as days from sowing until 90%–95% of pods reached physiological maturity, indicated by pod color change and seed hardening, not based on leaf senescence or threshing ease.

2.4.3.2 | Vegetative Growth Parameters

- Number of primary branches: Recorded from 10 randomly selected plants at physiological maturity.
- Plant height (cm): Measured from ground level to the top of the main stem (not panicle) from 10 randomly selected plants and averaged.

2.4.3.3 | Yield and Yield Components of Legumes

- Number of pods per plant: Recorded from 10 randomly selected plants per plot and averaged.
- Number of seeds per pod: Recorded from a subsample of pods taken from 10 randomly selected plants and averaged.
- Hundred-seed weight (HSW) (g): Determined using a random cleaned seed subsample, counted with a seed counter, and weighed, then adjusted to standard moisture content.
- Aboveground dry biomass: Harvested from the net plot and oven-dried at 70°C to constant weight before measurement.
- Grain yield (kg ha^{-1}): Determined from the net plot area and adjusted to 10% standard grain moisture content.
- Straw yield (kg ha^{-1}): Calculated as total aboveground dry biomass minus grain yield (dry basis).
- HI (%): Calculated as grain yield divided by aboveground dry biomass × 100.

2.5 | Assessment of Biological and Economical Benefits of Intercropping

According to Willey [11], the productivity of the intercropping system was determined by calculating the LER, which is the relative land area required as a sole crop to produce the same yield as an intercrop system:

$$\mathrm{LER} = \frac{\mathrm{Yab}}{\mathrm{Yaa}} + \frac{\mathrm{Yba}}{\mathrm{Ybb}}, \tag{1}$$

where

$$\begin{aligned} \mathrm{Yab} &= \text{Yield per unit area of crop a in intercropping,} \\ \mathrm{Yaa} &= \text{Yield per unit area of crop in a sole cropping,} \\ \mathrm{Yba} &= \text{Yield per unit area of crop b in intercropping,} \\ \mathrm{Ybb} &= \text{Yield per unit area of crop b in sole cropping.} \end{aligned} \tag{2}$$

In other ways, LER can be calculated as the formula; LER= La + Lb, where La and Lb are the partial LERs for the individual crop. The comparison between the partial LERs (La + Lb) can indicate the competitiveness of the individual species, and the total LER is a measure of the relative yield advantage. LER value > 1.00 indicates an agronomic advantage of intercropping over sole cropping.

Monetary advantage index (MAI) was used to measure economic advantage. Accordingly, MAI was calculated by multiplying the respective yields of the component crops by their lowest market

prices during the experiment and dividing by the respective LER. MAI = (value of combined intercrops) (LER-1)/LER; the higher the MAI value, the more profitable the cropping system is. Since there is high market price fluctuation, the values of the combined intercrops in each cropping system were the lowest prevailing market prices of each component crop in Ethiopian birr per kg at the time of the experiment. The price of the component crop at Kobo woreda after harvest of the crops was 6 birr for sorghum, 35 birr for soybean, and 25 birrs for haricot bean. Intercropping advantage values indicate the disadvantage of the system as the MAI values were negative. Thus, a more satisfactory use of monitory values would probably be to calculate the absolute value of the genuine yield advantage [11].

2.6 | Statistical Data Analysis

Data were subjected to analysis of variance (ANOVA) using the generalized linear model (GLM) procedure of SAS 9.2 Version. Whenever the treatment differences are significant, means were compared using the least significant difference test at 1% or 5% level of significance.

Correlation analysis was carried out by calculating simple correlation coefficients among growth, yield, and yield components.

3 | Results and Discussion

3.1 | Striga Count m^{-2} as Influenced by Intercropping Time of Soybean and Haricot Bean With Sorghum

The ANOVA showed that Striga count was significantly different ($p < 0.01$) due to the main effects of intercropped legume type and sowing time. However, no significant interaction effect ($p > 0.05$) was observed between legume crops and their intercropping time. The lower *Striga* populations observed in sorghum plots intercropped with legumes compared to sole sorghum are consistent with recent findings that legume intercropping, including common bean, cowpea, and soybean, significantly reduced *Striga hermonthica* infestation and improved sorghum yield [12]. This may be attributed to differences in root exudates or host compatibility, as haricot bean appeared to have a higher suppressing effect on Striga germination than soybean.

The lower Striga populations observed in sorghum plots intercropped with haricot bean compared to those intercropped with soybean are consistent with the findings of [12]. This variation suggests potential differences in the effectiveness of root exudates or host compatibility between the two legumes; in this study, haricot bean demonstrated a greater suppressive effect on *Striga* germination than soybean.

Intercropping legumes 2 weeks or 1 week prior to sorghum sowing resulted in lower *Striga* counts per m^2 compared to simultaneous sowing (Figure 2). These results suggest that establishing legumes before the cereal crop may enhance the suppression of *Striga* germination, with the effect appearing more pronounced as the lead time increases. This trend aligns with [13], who reported lower *Striga* populations when legumes were established early. Conversely, some research has shown that although cereal–legume intercropping tends to reduce *Striga hermonthica* emergence relative to sole cropping, not all legume intercrops consistently produce significantly lower *Striga* counts in every season, suggesting that the effect of intercropping or its timing on *Striga* suppression can vary with species and environmental conditions [14].

Sole sorghum plots exhibited higher *Striga* density than all intercropped treatments, regardless of the intercropping period (Figure 2). This result agrees with Degebasa et al. [12], who reported higher *Striga* infestations in sole sorghum than in sorghum-legume systems. This observation is consistent with the role of sorghum as a primary host that produces stimulants, such as strigolactones, which initiate *Striga* germination. As noted by [10], the effectiveness of cereal-legume intercropping in reducing *Striga* germination likely depends on a combination of factors,

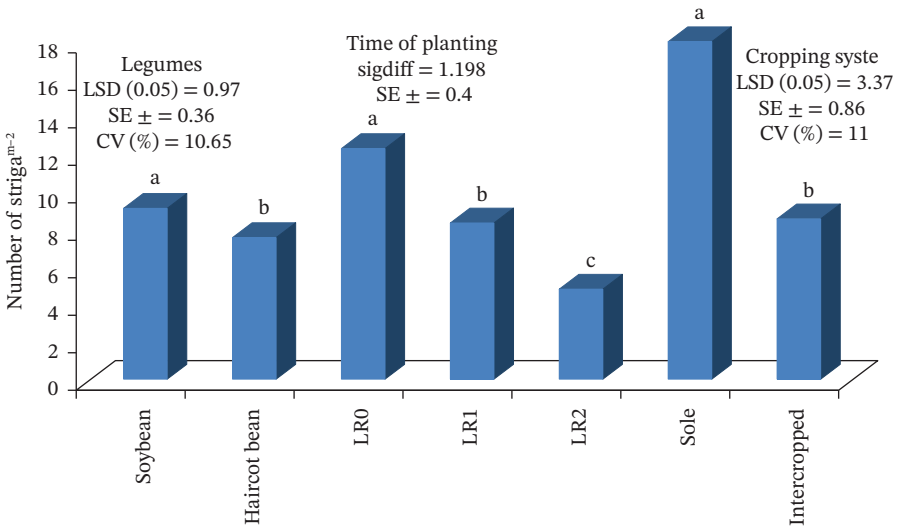


FIGURE 2 | Main effect of legume crops and time of planting on the number of Striga m^{-2} in intercropping of soybean and haricot bean with sorghum in the 2016 cropping season at Kobo. Notes: LR0 = at the same date with sorghum, LR1 = before one week of sorghum sowing, LR2 = before two weeks of sorghum sowing. Means followed by the same letter(s) within a column are not significantly different at the 5% probability level ($p < 0.05$), NS = not significant, LSD = least significant difference, CV = coefficient of variation, and SE: standard error of the mean.

including the production of germination stimulants by the intercrop (suicidal germination), root development patterns, and potential shading effects.

3.2 | Sorghum Phenology

The ANOVA showed that the main effect and interaction of legumes and their time of planting did not significantly influence days to heading and maturity (Table 3). However, the sole sorghum produced flowers and matured significantly delayed. This is due to the reason that in sole sorghum, the Striga density was high and created competition for resources.

3.3 | Vegetative Growth Parameters of the Component Crops as Influenced by Intercropping Time of Soybean and Haricot Bean With Sorghum

3.3.1 | Vegetative Growth of Sorghum

3.3.1.1 | Plant Height. The ANOVA revealed that sorghum plant height was significantly ($p < 0.01$) influenced by the main effects of intercrop legume species and sowing time; however, no significant interaction ($p > 0.05$) was observed between these two factors. Sorghum intercropped with soybean attained a mean height of 235.9 cm, while sole sorghum attained a mean height of 203.0 cm. On average, sorghum grown under intercropping systems (224.4 cm) was taller than in sole stands (Table 4).

Among the intercropping treatments, sorghum grown with soybean was taller (235.9 cm) than that grown with haricot bean. Regarding the timing of legume introduction, sowing legumes 2 weeks before sorghum resulted in a mean height of 233.0 cm, which was greater than the height observed under simultaneous planting. The variation in height between the two legume intercrops may be associated with differing competitive abilities or growth habits of the species. However, as resource capture was not directly quantified in this study, these differences remain a subject for further investigation.

Previous studies have reported inconsistent effects of intercropping on cereal plant height. For instance, some maize–legume intercropping experiments showed that including legumes such as common bean or soybean did not significantly alter maize growth parameters, including plant height, compared with sole maize cropping [15, 16]. These findings suggest that the impact of intercropping on cereal height is influenced by environmental conditions, specific genotype combinations, and management practices. The taller growth observed in the present study under certain intercropping regimes indicates that the competitive dynamics in Kobo may differ from those reported in previous studies.

3.3.1.2 | Panicle Length. The ANOVA showed that panicle length was significantly ($p < 0.05$) influenced by legume species; however, neither sowing time nor the interaction of factors had a significant effect (Table 4). Sorghum intercropped with soybean produced mean panicle lengths of 27.3 cm, whereas those intercropped with haricot bean averaged 22.2 cm.

While sole sorghum produced shorter panicles compared to the intercropped treatments, the specific physiological reasons for this were not quantified in this study. The observed variation in panicle length between the two legume systems suggests that the choice of intercrop species can influence reproductive growth

TABLE 3 | Main effect of legume crops and time of planting on phenological parameters of sorghum, intercropping with soybean and haricot bean.

Treatments	Days to heading	Days to maturity
Legumes		
Soybean	75.00	119.22
Haricot bean	75.44	120.44
LSD (0.05)	1.51	1.97
SE ±	0.45	0.60
Time of sowing		
Before 2 weeks of sorghum sowing	75.33	119.17
Before 1 week of sorghum sowing	74.83	120.33
At the same date with sorghum	75.50	120[a]
LSD (0.05)	**1.84**	**2.41**
SE ±	**0.56**	**0.73**
CV (%)	**1.64**	**1.36**
Cropping system		
Intercropped sorghum	75.22[b]	120.00[b]
Sole sorghum	80.33[a]	124.7[a]
LSD (0.05)	**2.53**	**2.54**
SE ±	**0.65**	**0.65**
CV (%)	**1.44**	**0.9**

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. SE: standard error of the mean. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; LSD, least significant difference; NS, not significant.

TABLE 4 | Effect of legume crops and time of planting on vegetative growth parameters of sorghum, intercropped with soybean and haricot bean.

Treatments	Plant height	Panicle length
Legumes		
Soybean	235.88[a]	27.33[a]
Haricot bean	213.00[b]	22.22[b]
LSD (0.05)	**7.53**	**4.3**
SE ±	**2.28**	**1.40**
Time of sowing		
Before 2 weeks of sorghum sowing	233.16[a]	27.5
Before 1 week of sorghum sowing	220.00[b]	25.00
At the same date with sorghum	220.16[b]	21.83
LSD (0.05)	**9.2**	**5.3**
SE ±	**3.95**	**1.72**
CV (%)	**3.19**	**17.2**
Cropping system		
Intercropped sorghum	224.44[a]	24.8[a]
Sole sorghum	203.00[b]	20.7[a]
LSD (0.05)	**4.57**	**4.84**
SE ±	**1.16**	**1.2**
CV (%)	**1.00**	**9.4**

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. SE: standard error of the mean. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; LSD, least significant difference; NS, not significant.

components of sorghum, a finding that aligns with [17], who also reported variations in panicle length based on the specific legume companion used. However, further research involving the measurement of light interception and nutrient uptake would be required to confirm whether these differences stem from varying levels of interspecific competition.

3.3.2 | Vegetative Growth of Soybean Plant

3.3.2.1 | Plant Height. The ANOVA indicated that soybean plant height was significantly ($p < 0.01$) influenced by the time of planting (Table 5). The tallest soybean plants (68.2 cm) were recorded when the legume was established 2 weeks prior to

TABLE 5 | Main effect of planting time on vegetative growth parameters of soybean and haricot bean, soybean, and haricot bean intercropped with sorghum.

Time of planting	Soybean		Haricot bean	
	PH	NPB	PH	NPB
Before 2 weeks of sorghum	68.20[a]	4.33[a]	31.03	3.33
Before 1 week of sorghum sowing	59.43[b]	3.00[b]	30.77	3.33
At the same date with sorghum	57.33[b]	3.00[b]	30.23	3.33
LSD (0.05)	**5.1**	**0.66**	**3.6**	**1.15**
SE ±	**1.47**	**0.19**	**1.16**	**0.41**
CV (%)	**4.14**	**9.6**	**5.58**	**17.34**
Cropping system				
Intercropped soybean	62.05[b]	3.33 b	30.7	3.33
Sole soybean	68.33[a]	4.00[a]	32.7	4.2
LSD (0.05)	**3.01**	**0.4**	**2.25**	**1.57**
SE ±	**0.97**	**0.1**	**1.3**	**0.47**
CV (%)	**2.6**	**0.3**	**6.6**	**22.0**

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; LSD, least significant difference; NPP, number of primary branches; NS, not significant; PH, plant height.

sorghum, whereas the shortest plants (52.1 cm) were observed under simultaneous planting. On average, sole soybean reached a maximum height of 68.3 cm, while intercropped soybean averaged 62.1 cm (Table 5).

The observed reduction in height under intercropping suggests a response to the presence of the taller sorghum canopy. This trend may be associated with interspecific competition for growth factors such as light; however, since resource capture and light interception were not measured in this study, these factors remain potential explanations rather than confirmed causes. The taller stature and canopy architecture of sorghum typically position it as the dominant component in these mixtures. Comparable studies in maize–soybean intercropping systems have found that modifications in planting time or intercropping arrangements may have minimal impact on the height of the shorter component crop, suggesting that species-specific traits and local environmental conditions strongly influence morphological responses [18].

3.3.2.2 | Number of Primary Branches. The number of primary branches per plant was significantly ($p < 0.01$) affected by planting time (Table 5). The maximum number of branches (4.3) was obtained when soybean was sown 2 weeks before sorghum. Sole soybean produced a higher number of branches (4.0) compared with intercropped soybean (3.3) (Table 5).

The observed reduction in branching under intercropping suggests that the presence of sorghum may have influenced the vegetative development of the soybean component. While this trend is often attributed to competition for growth resources, resource capture was not specifically quantified in this study. Therefore, the reduction in branching capacity remains a potential response to the intercropping environment rather than a confirmed result of specific resource limitation.

3.3.2.3 | Haricot Bean Vegetative Growth. Plant height of haricot bean did not significantly influence due to the time of planting.

Number of primary branches did not show significant ($p \geq 0.05$) effect due to the time of planting.

3.4 | Yield and Yield-Related Traits of Component Crops as Influenced by Intercropping Time of Soybean and Haricot Bean With Sorghum

3.4.1 | Yield and Yield-Related Traits of Sorghum

3.4.1.1 | Head Weight Per Plant. Sorghum head weight per plant was highly significantly affected by the main effect of legume species ($p < 0.01$) and significantly influenced by sowing time ($p < 0.05$); however, the interaction effect was not significant (Table 6). Sorghum intercropped with legumes recorded a higher mean head weight (69.8 g) compared to sole sorghum (62.5 g). The greater head weight observed in the present study is consistent with research, showing that intercropping sorghum with legumes significantly reduced *Striga hermonthica* infestation and enhanced sorghum productivity, likely alleviating parasitic stress that otherwise limits growth and yield components in sole stands [12]. Planting legumes 2 weeks prior to sorghum resulted in the highest head weight (75.7 g). In the present study, the soybean–sorghum intercrop yielded a higher mean head weight (74.7 g) than the haricot bean–sorghum

TABLE 6 | Effect of legumes and time of intercropping on yield and yield components of sorghum.

Treatments	HW	1000 SW	GY/plant	BMY (kg ha^{-})	GY (kg ha^{-})	SY (kg ha^{-})	HI (%)
Legumes							
Soybean	74.55^{a}	39.99^{a}	48.48^{a}	20606.55^{a}	2053.90^{a}	18552.61^{a}	9.9^{a}
Haricot bean	65.00^{b}	33.30^{b}	43.40^{b}	18451.45^{b}	1439.40^{b}	17012.03^{a}	7.8^{a}
LSD (0.05)	**2.83**	**3.27**	**3.5**	**1645**	**346**	**1756.3**	**2.01**
SE±	**1.7**	**1.2**	**1.27**	**490.23**	**109.56**	**523.0**	**0.60**
Time of planting							
Before 2 weeks of sorghum sowing	75.66^{a}	39.94^{a}	50.19^{a}	21696.9^{a}	2068.00^{a}	19628.87^{a}	9.53^{a}
Before 1 week of sorghum sowing	68.33^{b}	36.14^{ab}	44.7^{b}	19570.76^{b}	1702.90^{ab}	17867.87^{ab}	8.70^{a}
At the same date with sorghum	65.33^{b}	34.00^{b}	42.91^{b}	17319.31^{c}	1469.10^{b}	15850.22^{b}	8.48^{a}
LSD (0.05)	**3.47**	**4.00**	**4.27**	**2015.6**	**424**	**2150.9**	**2.63**
SE±	**2.1**	**1.5**	**1.56**	**600.4**	**134.2**	**640.3**	**0.8**
CV (%)	**3.87**	**8.5**	**7.23**	**8.02**	**18.88**	**9.40**	**22.95**
Cropping system							
Intercropped sorghum	69.8^{a}	36.6^{a}	45.9^{a}	19529^{a}	1746.7^{a}	17782.3^{a}	8.9^{a}
Sole sorghum	62.3^{b}	30.9^{b}	40.9^{b}	17950.6^{b}	1336.4^{b}	16614.2^{b}	7.4^{a}
LSD (0.05)	**7.4**	**4.17**	**4.9**	**721**	**310**	**901**	**1.84**
SE ±	**1.92**	**1.0**		**183.84**	**79.11**	**229.51**	**0.5**
CV (%)	**5.0**	**5.4**	**4.9**	**1.7**	**8.9**	**2.3**	**9.90**

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. SE: standard error of the mean, 1000SW: thousand-seed weight, BMY: biomass yield, GY/plant: grain yield per plant, HW: head weight per plant. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables. Abbreviations: CV, coefficient of variation; GY, grain yield; HI, harvest index; LSD, least significant difference; NS, not significant; SY, straw yield.

mixture, indicating that the identity of the legume intercrop can influence sorghum reproductive performance. These differences likely reflect species-specific interactions that affect resource use and competitive balance within the mixed stand. Since measurements of light interception and resource capture were not performed, the exact physiological mechanisms behind these variations remain uncertain and merit further investigation [19].

3.4.1.2 | Thousand-Seed Weight (TSW). TSW was significantly influenced by legume species ($p < 0.01$) and sowing time ($p < 0.01$), with no significant interaction effect observed between the two factors. Sorghum intercropped with legumes produced a higher TSW (36.6 g) compared to sole sorghum (30.9 g) (Table 6). This increase is consistent with the lower *Striga* pressure recorded in the intercropped plots, which likely reduced host stress during the grain-filling stage [13].

The benefits of earlier establishment of legumes have been attributed to altered competitive dynamics and improved resource partitioning in cereal–legume intercrops, where species-specific growth traits influence the balance between competition and complementarity [19].

3.4.1.3 | Grain Yield per Plant. Sorghum grain yield per plant was significantly influenced by the choice of intercropped legume species ($p < 0.05$); however, the interaction between legume type and sowing time was not significant (Table 6). Sorghum intercropped with soybean produced a higher grain yield (48.5 g) compared to those intercropped with haricot bean.

The highest grain yield per plant (50.2 g) was achieved when legumes were established 2 weeks prior to sorghum. This observation is consistent with the reduced *Striga* infestation recorded in these treatments, which likely alleviated the parasitic burden on the sorghum plants during critical growth stages [13]. While these results suggest a more favorable environment for grain production in early intercropped systems, further study is required to quantify the specific improvements in resource use efficiency, as these parameters were not directly measured.

3.4.1.4 | Aboveground Dry Biomass Yield. Sorghum aboveground dry biomass was significantly influenced ($p < 0.01$) by both legume species and sowing time, with no significant interaction observed between these factors. Intercropping with legumes increased the biomass yield to 19,529 kg/ha, compared to 17,529 kg/ha in sole sorghum stands (Table 6). This increase is consistent with the recorded reduction in *Striga* interference, which likely enhanced the overall vegetative growth of the host plants [13].

Among the legume types, soybean–sorghum intercrops produced a biomass of 20,607 kg/ha, whereas haricot bean–sorghum intercrops yielded 18,451 kg/ha. The variation in biomass may be associated with the differing morphological and growth habits of the two legume species. While earlier research suggests that differences in canopy coverage and resource competition can influence cereal biomass [20], specific light and nutrient measurements were not conducted in this study to confirm these causal mechanisms.

Furthermore, planting legumes two weeks prior to sorghum resulted in the maximum biomass yield of 21,697 kg/ha. Early establishment of the legume component is associated with effective *Striga* suppression during the critical vegetative growth stages of sorghum [10]. These results suggest that lead-time sowing provides a more favorable environment for sorghum biomass accumulation compared to simultaneous planting.

3.4.1.5 | Straw Yield. Sorghum straw yield was highly significantly influenced by sowing time ($p < 0.01$). The maximum straw yield was achieved when legumes were established 2 weeks prior to sorghum sowing. These results suggest that the timing of legume introduction plays a critical role in the vegetative development of the cereal component.

The higher straw yield observed with early legume sowing is consistent with findings by [13], who noted improved cereal performance under staggered planting dates. While such increases are often associated with reduced interspecific competition during early growth stages, the specific dynamics of resource capture were not quantified in this study. Therefore, the observed yield increase reflects a more favorable growing environment provided by the lead-time sowing of the legume component.

3.4.1.6 | Grain Yield. Sorghum grain yield was highly significantly influenced by legume species ($p < 0.01$) and significantly influenced by sowing time ($p < 0.05$); however, their interaction effect was not significant. Intercropping with legumes increased the mean grain yield to 1747 kg/ha, compared to 1336 kg/ha in sole sorghum stands (Table 6). This increase is consistent with the observed reduction in *Striga* density, which likely decreased the parasitic pressure on the cereal component [13].

Among the legume species, soybean–sorghum intercrops achieved a grain yield of 2054 kg/ha, compared with 1439 kg/ha for haricot bean–sorghum mixtures. These differences suggest that the two legumes interact differently with sorghum, potentially due to variation in competitive ability and resource use between species. Differences in canopy structure, resource capture, and competitive dominance have been documented in cereal–legume intercrops, where tall soybean cultivars can outcompete shorter companions for light and nutrients, influencing cereal yield outcomes, whereas other legumes may exhibit distinct architecture and competitive behavior that alters interspecific interactions [21, 22]. Furthermore, early intercropping of legumes two weeks before sorghum sowing resulted in the maximum grain yield of 2068 kg/ha. This yield advantage is associated with the early establishment of the legume component, which appeared to suppress *Striga* more effectively than simultaneous planting. This timing likely provides a more favorable growing environment during critical stages of sorghum development, thereby contributing to the observed yield increase.

3.4.1.7 | HI. HI was significantly influenced by the choice of legume species ($p < 0.05$); however, the time of sowing did not show a significant effect (Table 6). The highest HI values were recorded in soybean–sorghum combinations. This result is primarily a reflection of the higher grain yield relative to the total aboveground biomass produced in these plots. While intercropping systems are frequently recognized for their potential to optimize resource utilization, including light, water, and nutrients, the present study did not directly measure nutrient uptake,

photosynthetic efficiency, or water-use efficiency. Consequently, the observed differences in HI are interpreted as shifts in biomass partitioning toward grain production in response to specific legume companions, rather than as confirmed alterations in resource capture or physiological efficiency. Previous studies in cereal–legume intercropping systems have documented that variations in companion species can influence growth allocation patterns and yield components, even in the absence of measured changes in resource use efficiency [19, 21].

3.4.2 | Yield and Yield Components of Soybean

3.4.2.1 | Number of Pods Per Plant. The number of pods per soybean plant was significantly influenced by planting time ($p < 0.05$). Intercropping soybean 2 weeks prior to sorghum produced the highest pod number (25.7 pods per plant), whereas the lowest numbers were observed under simultaneous sowing (Table 7). The pod count for soybean sown 1 week before sorghum was statistically at par with the 2-week lead time.

The increased pod production in early-established soybean suggests that allowing legumes a lead time before sorghum created conditions more favorable for reproductive development than simultaneous planting. Early establishment of one intercrop relative to another can alter competitive interactions, potentially improving access to light and soil resources during key growth phases, although these physiological drivers were not directly quantified in the present study. Such effects of temporal sowing differences on intercrop performance have been demonstrated in cereal–legume systems, where sowing the legume component earlier or adjusting the timing of intercrop establishment influenced both yield components and the relative performance of the component crops [23].

3.4.2.2 | Number of Seeds Per Pod. Seeds per pod were not significantly affected by planting time ($p > 0.05$). Soybean grown alone did not produce more seeds per pod than intercropped soybean, indicating that seed number per pod is relatively stable regardless of competition or cropping arrangement (Table 7).

3.4.2.3 | HSW. HSW of soybean was significantly influenced by planting time ($p < 0.05$). Soybean intercropped 2 weeks before sorghum recorded the highest HSW (17.0 g), whereas simultaneous sowing with sorghum resulted in the lowest weight (14.1 g) (Table 7).

The higher seed weight observed in early-planted soybean suggests a more favorable growth environment during the seed-filling period. While this trend is commonly attributed to enhanced capture of light and nutrients, the present study did not directly measure such physiological parameters. Sole soybean produced a maximum HSW of 18.0 g, which aligns with observations from maize–soybean intercropping experiments that report variation in soybean yield components under different intercropping conditions [24]. The difference between sole and intercropped soybean may be linked to interspecific competition for shared resources, although without direct quantification of nutrient or light use, this remains an area for further investigation.

3.4.2.4 | Aboveground Biomass. The aboveground biomass of soybean was significantly affected by planting time ($p < 0.05$). The greatest biomass was recorded when soybeans were sown 2 weeks before sorghum (Table 7), whereas simultaneous sowing resulted in reduced biomass accumulation.

This trend suggests that early establishment allows for a longer period of vegetative growth before the cereal component becomes dominant. While such an advantage is often attributed to improved resource capture, specific measurements of light interception, nutrient uptake, or water use were not conducted in this study. Therefore, the increased biomass is reported here as an observed response to the sowing lead time, rather than a confirmed result of specific resource dynamics. These findings are consistent with the general principle that staggered planting can alter the competitive balance in intercropping systems, though the exact physiological drivers in this environment require further quantification.

3.4.2.5 | Grain Yield. Soybean grain yield was significantly influenced by the time of planting ($p < 0.05$). Early intercropping, established 2 weeks before sorghum, produced the highest yield (552.6 kg/ha), whereas simultaneous sowing resulted in the lowest yield (207.2 kg/ha) (Table 7).

The increased yield observed with early planting suggests a more favorable period for crop establishment and reproductive growth before the sorghum canopy becomes dominant. While such yield advantages are often linked to improved competitive ability for growth resources, this study did not directly quantify light interception, nutrient uptake, or moisture levels. Consequently, the reduction in yield observed with delayed planting is consistent with the findings of [23], though the specific contribution of competition or environmental stress in this context remains a subject for further investigation.

3.4.2.6 | Straw Yield. Soybean straw yield was significantly affected by the timing of planting ($p < 0.05$). The data show that delayed planting (simultaneous sowing with sorghum) resulted in a lower straw yield compared to earlier establishment dates.

This reduction suggests that the timing of introduction into the intercropping system significantly influences the vegetative development of the soybean component. While literature often attributes such decreases to interspecific competition for resources or canopy shading, these factors were not directly quantified in this study. Therefore, the observed lower straw yield is reported as a response to the intercropping environment, with further research required to determine the specific contribution of resource limitation or light availability to this outcome.

3.4.2.7 | HI. HI was significantly influenced by planting time ($p < 0.05$). The highest HI (45.82) occurred with early intercropping (2 weeks before sorghum), while the lowest (33.11) was recorded with simultaneous sowing (Table 7). Early planting allows better allocation of assimilates to seeds rather than vegetative tissues, improving HI.

3.4.3 | Yield and Yield Components of Haricot Bean

3.4.3.1 | Number of Pods Per Plant. ANOVA showed that the number of pods per plant was significantly affected by the time of planting ($p < 0.05$). Additionally, a significant difference

TABLE 7 | Main effect of intercropping of time of soybean on yield components and yield of soybean, soybean intercropped with sorghum.

Treatments	NPP	NSPP	100 SW (g)	BMY (kg ha^{-})	GY (kg ha^{-})	SY (kg ha^{-})	HI (%)
Time of planting							
Before 2 weeks of sorghum sowing	25. 66^{a}	3.33^{a}	16.95^{a}	1197.22^{a}	552.57^{a}	644.64^{a}	45.82^{a}
Before 1 week of sorghum sowing	23.00^{a}	3. 00^{a}	16.15^{a}	1030.16^{a}	404.22^{ab}	625.93^{a}	38.80^{ab}
At the same with sorghum	17.00^{b}	2.8^{a}	14.12^{b}	631.74^{b}	207.20^{b}	424.54^{b}	33.11^{b}
SE ±	**1.64**	**0.27**	**0.5**	**106.36**	**60.2**	**53.01**	**2.13**
LSD (0.05)	**5.69**	**0.94**	**1.76**	**368**	**208**	**183.46**	**7.39**
CV (%)	**13.01**	**15.7**	**5.62**	**19.32**	**26.85**	**16.25**	**9.43**
Cropping system							
Intercropped	21.88^{a}	3.0^{a}	15.7^{b}				
Sole cropped	26.00^{a}	3.3^{a}	18.0^{a}				
LSD (0.05)	**4.18**	**0.66**	**2.09**				
SE ±	**1.04**	**0.63**	**0.87**				
CV (%)	**7.70**	**12.89**	**8.9**				

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. SE: standard error of the mean. 1000SW: thousand-seed weight, SY: straw yield; BMY: biomass yield, GY/plant: grain yield per plant, HW: head weight per plant, 100SW: hundred-seed weight, BMY: biomass yield, NPP: number of pods per plant, NSPP: number of seeds per pod. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; GY, grain yield, HI, harvested index; LSD, least significant difference; NS, not significant; SY: stalk yield.

in pods per plant was observed between the intercropped and sole haricot bean. However, no significant interaction effect ($p > 0.05$) was observed between legume species and sowing time.

The results of the present study contrast with some earlier findings in cereal–legume intercropping research. For example, maize–cowpea intercrops have been reported to influence cowpea pod production under certain intercropping ratios, but the direction and magnitude of the effect can differ depending on spacing and management [25]. In other experiments where component crops were evaluated under varied cereal–legume intercropping arrangements, pod numbers per plant did not always differ significantly between sole and intercropped legumes, indicating that environmental conditions and species interactions can moderate reproductive responses. These varying results suggest that legume reproductive outcomes in intercrops are highly dependent on the specific crop combinations, spatial arrangements, and agroecological conditions. Because this study did not directly quantify competitive dynamics or resource capture mechanisms in the sorghum–haricot bean system, such physiological explanations remain hypotheses warranting further investigation.

3.4.3.2 | Number of Seeds Per Pod. The ANOVA showed that the number of seeds per pod was highly significantly affected by the time of planting ($p < 0.01$). The maximum number of seeds per pod (4.6) was recorded when haricot bean was intercropped 2 weeks before sorghum, while the minimum (3.0) was recorded under simultaneous planting (Table 8). The results for simultaneous planting were statistically at par with those for planting 1 week before sorghum.

These findings partly agree with [26], who reported that sowing time influenced seeds per pod in maize–cowpea systems. However, that study found that simultaneous planting increased seeds per pod, whereas the current study observed the opposite trend. This discrepancy indicates that reproductive responses to sowing time vary significantly depending on the specific crop combination and environmental context. The higher number of seeds per pod in early-established haricot bean suggests that a longer period of establishment prior to the cereal's peak growth period is beneficial for seed set. While a reduction under delayed planting may be associated with increased interspecific competition, it is important to note that resource competition was not directly measured in this study; therefore, this explanation remains a hypothesis and should be interpreted with caution.

3.4.3.3 | Aboveground Biomass. Aboveground dry biomass was significantly influenced by the time of planting ($p < 0.05$). The maximum biomass yield (2450 kg/ha) was obtained when haricot bean was intercropped with sorghum two weeks prior to cereal sowing, while the minimum (1910 kg/ha) was recorded under simultaneous planting (Table 8). These values have been rounded to a degree of precision consistent with field measurement techniques, as excessive decimals can reduce scientific credibility.

The observed reduction in biomass under simultaneous planting suggests a potential impact of interspecific interaction during the early vegetative stages. While such trends are often attributed to competition for nutrients, water, and light, these parameters were not directly measured in the present study. Furthermore, it should be noted that the biomass from simultaneous planting was statistically similar to other planting dates; therefore, the difference between the maximum and minimum recorded values should be interpreted as an indicative trend rather than a definitive causal outcome.

3.4.3.4 | Grain Yield of Haricot Bean. The ANOVA revealed that the grain yield of haricot bean was highly significantly affected by the time of planting ($p < 0.01$). The highest grain yield (1150 kg/ha) was recorded when haricot bean was intercropped with sorghum two weeks prior to the cereal sowing (Table 8). Additionally, the cropping system showed a significant

TABLE 8 | Main effect of intercropping of time of haricot bean on yield components and yield of haricot bean, haricot bean intercropped with sorghum.

Treatments	NPP	NSPP	100sw (g)	BMY (kg ha^{-})	GY (kg ha^{-})	SY (kg ha^{-})	HI (%)
Time of planting							
Before 2 weeks of sorghum sowing	23.00^{a}	4.6^{a}	39.99^{a}	2419.05^{a}	1151.11^{a}	1268.9^{a}	47.76^{a}
Before 1 week of sorghum sowing	18.33^{b}	3.33^{b}	37.55^{a}	2019.00^{b}	995.87^{b}	1023.2^{a}	49.35^{a}
At the same with sorghum	15.00^{b}	3.00^{b}	36.53^{a}	1910.30^{b}	776.39^{c}	1133.9^{a}	40.65^{b}
LSD (0.05)	**4.66**	**0.94**	**8.2**	**317**	**136**	**264**	**6.07**
SE ±	**1.34**	**0.43**	**0.2**	**91.63**	**39.3**	**76.53**	**1.53**
CV (%)	**12.42**	**12.85**	**10.68**	**7.50**	**7.00**	**11.6**	**6.62**
Cropping system							
intercropped	18.77^{b}	3.7^{a}	38.00^{a}				
Sole cropped	26.7^{a}	4.58^{a}	40.33^{a}				
LSD (0.05)	**2.35**	**1.08**	**3.05**				
SE ±	**0.63**	**1.03**	**0.90**				
CV (%)	**4.56**	**11.51**	**3.9**				

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. LSD = least significant difference, SE: standard error of the mean, 100SW: thousand-seed weight, BMY: biomass yield, NPP: number of pods per plant, NSPP: number of seeds per pod. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; NS, not significant; SY: stalk yield.

main effect on grain yield, while the interaction effect between the two factors was not significant ($p > 0.05$).

Grain yield significantly decreased to approximately 780 kg/ha when haricot bean was intercropped simultaneously with sorghum. This finding differs from Kussie et al. [25], who reported that simultaneous planting increased cowpea yield in maize cowpea systems. These contrasting results reinforce the observation that yield responses in intercropping are highly specific to the species combinations and local environmental conditions. While the yield advantage in early-planted plots is consistent with a longer establishment phase for the legume, the specific physiological drivers such as resource capture or reduced competition were not directly quantified in this study.

3.4.3.5 | HI. The HI of haricot bean was significantly affected by the time of planting ($p < 0.05$). The highest HI (49.4) and the lowest HI (40.7) were recorded from haricot bean sown 1 week before sorghum and simultaneous sowing, respectively (Table 8).

Higher HI values were observed in treatments where a larger proportion of total aboveground biomass was allocated to grain. Although greater yield is often associated with increased allocation to harvested organs, this study did not directly measure biomass partitioning or nutrient translocation. The observed variation in HI across different planting times likely reflects differences in the efficiency of assimilate allocation to grain under the competitive conditions of the intercrop. Recent studies have shown that HI is influenced by both environmental conditions and crop management practices, and that higher HI generally correlates with increased grain yield, while lower HI often coincides with reduced productivity [27–29]. These results suggest that sowing time can substantially affect the balance between vegetative growth and grain production, even in the absence of direct physiological measurements.

3.5 | Correlation of Growth and Yield Parameters of Component Crops as Influenced by Their Intercropping Time

3.5.1 | Correlation Among Important Agronomic Traits of Sorghum

TSW ($r = 0.64^{**}$), plant height ($r = 0.69^{**}$), panicle length ($r = 0.8^{**}$), TSW ($r = 0.64^{**}$), head weight, and biomass yield ($r = 0.61^{**}$) were highly significantly ($p < 0.01$) related in a positive sense with grain yield (Table 9). These growth and yield components exhibited highly significant ($p < 0.01$) positive correlations with aboveground dry biomass. These associations suggest that the variables are interlinked; however, these correlation coefficients represent associations between variables and should not be interpreted as evidence of a causal relationship (e.g., that an increase in one parameter directly caused the increase in another).

According to the present study, grain yield per plant and stalk yield ($r = 0.51^{*}$) also showed a significant ($p < 0.05$) positive correlation. Conversely, Striga density was negatively correlated with both grain yield and biomass yield (Table 9). In fact, most measured parameters exhibited a negative correlation with *Striga*, with the exception of sorghum phenological traits. This negative association indicates that increases in *Striga* infestation are statistically linked to decreases in sorghum growth and yield components, although the specific physiological mechanisms of this interference were not quantified in this study.

3.5.1.1 | Correlation Among Growth and Yield Parameters of Legumes. Soybean number of pods per plant, number of seeds per pod, stalk yield, and biomass yield were significantly ($p < 0.01$) and highly related in a positive sense with grain yield (Table 10). This significantly higher r-value indicates that there was strong evidence that those parameters in the intercropped proportions and crop types were strongly associated with each

TABLE 9 | Correlation among important agronomic traits of sorghum as influenced by intercropping time of soybean and haricot bean.

DE	DH	DM	PL	PH	1000 SW	SY	BMY	Yield	GY/plant	Weed	HI	HW
DE												
DH												
DM	−0.89*											
PL	0.21	−0.38										
PH	0.37	−0.50*	0.51*									
1000 SW	0.17	−0.18	0.59**	0.54*	0.72**							
SY	0.65**	−0.78**	0.50*	0.70**	0.46*							
BMY	0.63**	−0.75**	0.58**	0.74**	0.51*	0.99**						
Yield	0.24	−0.37	0.8**	0.69**	0.64**	0.51*	0.61**					
Yield/p	0.56**	−0.6**	0.57	0.72**	0.62**	0.69**	0.73**	0.63**				
Weed	0.76**	0.65**	−0.24	−0.23	−0.28	−0.71**	−0.69**	−0.81**	−0.51**			
HI	−0.27	0.22	0.52	0.24	0.38	0.21	−0.091	0.73**	0.18**	−0.36		
HW	0.61**	−0.73**	0.66**	0.71**	0.5**	0.77**	0.81**	0.73**	0.87**	−0.51**	0.19	

Note: DE: days to emergence, DM: days to maturity, 1000SW: thousand-seed weight, BMY: biomass yield, HW: head weight per plant.
Abbreviations: GY, grain yield; HI, harvested index; PH, plant height; PL, panicle length; SY, stalk yield.

TABLE 10 | Estimation of correlation between important agronomic traits of soybean and haricot bean over intercropping soybean–sorghum (lower from the diagonal shade) and haricot bean–sorghum (upper from the diagonal shade) intercropping system, respectively.

DE		DH	DM	PH	NPB	NPP	NSP	100SW	BMY	Yield	STY	HI
DE	1	0.83**	0.65	−0.37	0.32	0.68*	−0.52	−0.30	−0.77*	−0.87**	−0.37	−0.56
DH	−0.28	1	0.79**	−0.31	0.18	−0.56	0.79*	0.35	0.81**	−0.97**	−0.32	−0.71*
DM	0.64	0.37	1	0.22	−0.24	−0.49	−0.62	0.084	−0.57	−0.74*	−0.16	−0.61
PH	−0.68*	−0.04	−0.57	1	0.61	0.59	0.51	0.53	0.24	0.49	−0.12	0.54
NPB	−0.43	−0.33	−0.40	0.81**	1	0.09	0.35	0.46	0.27	0.27	0.18	0.12
NPP	−0.78*	−0.32	−0.86**	0.76*	0.66	1	0.33	0.07	0.34	0.62	0.11	0.65
NSP	−0.87*	−0.12	−0.81*	0.71*	0.66	0.92**	1	0.42	0.64	0.82**	0.19	0.67
100 SW	−0.56	−0.05	−0.78	0.73*	0.50	0.42	0.61	1	0.68*	0.47	0.66	0.01
BMY	−0.74*	−0.17	−0.61**	0.58	0.39	0.86**	0.84**	0.64	1	0.84**	0.80*	0.24
Yield	−0.79*	−0.18	−0.93**	0.61	0.48	0.87**	0.90**	0.64	0.97**	1	0.34	0.73*
STY	−0.62	−0.37	−0.88**	0.49	0.24	0.77*	0.69*	0.59	0.95**	0.87**	1	−0.40
HI	0.69*	−0.27	−0.71*	−0.46	−0.64	0.79*	0.88**	0.62	−0.44	0.36	−0.52	1

Note: DE: 50% date of emergency, DH: days to 50% flowering, DM: 50% date of maturity; 1000 SW: thousand-seed weight; BMY: biomass yield.
Abbreviations: PH, plant height; SY, stalk yield.
*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

other in a linear manner. According to the present study, grain yield was significantly ($p < 0.01$) and highly negatively correlated with days to maturity, and significantly ($p < 0.05$) correlated with days to emergence in a negative sense.

Biomass yield was significantly ($p < 0.01$) and highly correlated with the number of pods per plant, the number of seeds per pod, and stalk yield, in a positive sense. However, it was significantly correlated with plant height, HSW, and number of primary branches in a positive sense, and the phenological attributes were correlated with biomass yield negatively.

Haricot bean grain yield was highly significantly ($p < 0.01$) positively related to the number of pods per plant ($r = 0.82$**) and biomass yield ($r = 0.84$**). This indicates that those listed parameters had a strong relation in a linear way with the grain yield of haricot bean (Table 10).

3.6 | Effect of Intercropping Time of Soybean and Haricot Bean With Sorghum on Land Productivity and MAI

3.6.1 | LER

3.6.1.1 | Partial Equivalent Ratio (LER). The partial LER of sorghum exceeded 1.0 in all intercropping treatments, indicating that sorghum produced a higher yield per unit area when intercropped than when grown as a sole crop. In contrast, the partial LER values for the legumes were consistently less than 1.0. This is expected, as partial LER for a companion crop typically represents a fraction of its sole-crop performance and should not be compared against a threshold of 1.0 in isolation.

Within the intercropping treatments, the highest partial LER for sorghum (1.55) was recorded when legumes were planted 2

TABLE 11 | Partial land equivalent ratio, total land equivalent ratio of sorghum, soybean, and haricot bean intercropping.

Treatments	Sorghum	Legumes	LER
Legumes			
Soybean	1.53[a]	0.51[a]	2.04[a]
Haricot bean	1.07[b]	0.41[b]	1.48[b]
LSD	**0.25**	**0.068**	**0.25**
SE	**0.80**	**0.02**	**0.079**
Time of planting			
Before 2 weeks of sorghum sowing	1.55[a]	0.60[a]	2.15[a]
Before 1 week of sorghum sowing	1.24[ab]	0.45[b]	1.69[b]
At the same date with sorghum	1.09[b]	0.33[c]	1.42[b]
LSD (0.05)	**0.31**	**0.08**	**0.30**
SE ±	**0.10**	**0.027**	**0.097**
CV (%)	**18.8**	**14.55**	**13.52**

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. SE = standard error of the mean. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; LER, land equivalent ratio; LSD, least significant difference; NS, not significant.

TABLE 12 | Monetary advantage index of sorghum, soybean, and haricot bean intercropping.

Treatments	MAI
T1 = Soybean before 2 weeks of sorghum sowing	21804[a]
T2 = Soybean before 1 week of sorghum sowing	12433[b]
T3 = Soybean at the same date with sorghum	7009[c]
T4 = Haricot bean before 2 weeks of sorghum sowing	17916[a]
T5 = Haricot bean before 1 week of sorghum sowing	11400[cb]
T6 = Haricot bean at the same date with sorghum	6526[c]
T7 = Sole soybean	−1.27 days
T8 = Sole haricot bean	−1.60 days
T9 = Sole sorghum	0 days
LSD (0.05)	**5259.9**
SE ±	**1770.3**
CV (%)	**35.79**

Note: Means followed by the same letter(s) within column are not significantly different at $p < 0.05$ level of significance. SE = standard error of the mean. Values are bolded to distinguish the statistical analysis parameters (LSD at 5% level, SE ±, and CV%) from the treatment mean values, thereby improving the readability and interpretation of the statistical results presented in the tables.
Abbreviations: CV, coefficient of variation; LSD, least significant difference; NS, not significant.

weeks before sorghum sowing, while the lowest (1.09) occurred under simultaneous planting (Table 11). This suggests that earlier legume establishment was associated with improved sorghum performance.

This response may suggest temporal complementarity in the cropping system. However, as resource capture (nutrients, water, and light) and biological nitrogen fixation were not directly measured, these factors remain potential contributors rather than confirmed causes. Earlier planting of legumes was associated with higher total LER values, suggesting improved overall system productivity compared to simultaneous or delayed planting. In this study, the cereal component contributed a larger share to the intercrop yield than the legumes, supporting the role of legumes as a complementary rather than a dominant component in the system.

3.6.1.2 | Total LER and System Productivity. The total LER was greater than 1.0 in all intercropping treatments, demonstrating a yield advantage over monocropping. The maximum total LER (2.15) was achieved when legumes were intercropped 2 weeks before sorghum. An LER of 2.15 indicates that the intercropping system produced 2.15 times the yield of sole cropping on an equivalent land area, while higher LER values are often attributed to improved combined use of resources, such as light, land, and water.

The lowest total LER (1.42) was obtained under simultaneous planting. Across treatments, LER generally increased with earlier legume planting and decreased with delayed planting. Specifically, the soybean–sorghum combination achieved an LER of 2.04 (Table 11), indicating significant land-use efficiency compared to growing the crops separately.

3.6.2 | MAI

The MAI values were positive for all sorghum–legume combinations (Table 12), indicating a clear economic advantage compared to sole cropping systems. These results are supported by Dhima et al. [30], who reported that cereal–legume intercropping systems enhance productivity and competitive advantage compared to monocropping systems through improved resource utilization.

The positive MAI values further justify the practice of intercropping sorghum with legumes, as the system demonstrated higher profitability and economic resilience. Such results suggest that intercropping can improve overall system productivity and increase income for smallholder farmers [31].

The maximum MAI (21,804) was recorded in the soybean–sorghum combination when soybean was sown two weeks prior to sorghum. This higher value suggests that the early establishment of soybean is economically favorable within this specific cropping system. Conversely, the minimum positive MAI (6,526) (Table 12) was recorded for the haricot bean–sorghum combination under simultaneous sowing.

The variation in MAI between the two legumes is influenced by the market price of the components, where the higher price of soybean relative to haricot bean contributed to a more favorable index. Additionally, the results show that delaying the legume sowing time led to a reduction in MAI. While this reduction is often attributed to interspecific competition or less efficient resource use, these physiological interactions were not directly quantified in this study. Therefore, the lower MAI in delayed treatments is reported as an observed economic outcome of the sowing schedule rather than a confirmed result of specific biological competition.

4 | Conclusions and Recommendations

Sorghum production in Ethiopia's lowland areas is significantly constrained by poor agronomic practices and Striga infestation. This study evaluated the effect of cereal–legume intercropping and legume sowing time on Striga suppression and crop performance. Results revealed that intercropping sorghum with legumes, particularly when legumes were sown 2 weeks before sorghum, significantly reduced Striga emergence. Among the legume options, haricot bean was most effective in Striga suppression, while sole sorghum plots recorded the highest Striga counts. Although intercropping did not influence sorghum phenological traits, it markedly improved yield components, especially when soybean was used. Notably, soybean intercropped two weeks before sorghum planting enhanced plant height, biomass, TSW, and grain yield. Similarly, early planting of legumes led to better performance in both soybean and haricot bean in terms of growth and yield. The highest land-use efficiency (LER = 2.15) and economic return (21,804 birr) were achieved from soybean intercropped two weeks prior to sorghum. Therefore, intercropping legumes particularly soybean 2 weeks before sorghum sowing is recommended as an effective strategy to manage Striga and enhance sorghum productivity in Kobo and similar agroecological areas. However, to strengthen these findings and ensure wider applicability, further studies across multiple seasons and locations are recommended.

Author Contributions

Mohammed Hussen: conceptualization, experimental design, methodology development, field supervision, data analysis, interpretation of results, writing–original draft preparation, and manuscript revision.

Zeru Asefa: methodology refinement, field data collection supervision, validation of agronomic measurements, statistical analysis support, and manuscript review and editing.

Alemu Molla: field data collection, data curation, Striga infestation assessment, and contribution to writing and validation.

Endalkachew Fekadu: advanced interpretation of the revision section, validation of results, and critical technical revision.

Moges Tadesse: intercropping efficiency analysis, supervision support, and manuscript review and editing.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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