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Research Article

Plant Density and Time of White Lupine (*Lupinus Albus L.*) Relay Cropping with Tef (*Eragrostis tef* (Zucc.) Trotter) in Additive Design in the Highlands of Northwest Ethiopia

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Agronomic strategies such as choosing the optimal row ratio and planting legume crops at the right time are crucial for enhancing crop productivity. A field experiment was conducted in 2016 and 2017 to assess the influence of plant density and lupine intercropping time on tef field productivity. The treatments were as follows: tef was planted at a 20 cm inter-row spacing, lupine was sown at 20 and 40 cm inter-row spacing (row ratio of 1 tef: 1 lupine and 2 tef: 1 lupine) and lupine intercropped three times (1, 2, and 3 weeks after tef planting). Randomized complete block design (RCBD) with 3 replications were used. Two sole tef and lupine were planted. The results revealed 40 cm inter-row spacing and delayed lupine intercropping (3 weeks after tef planting) provided the maximum tef grain yield of 1.80 $t\,ha^{-1}$. The sole cropping of lupine produced the highest lupine grain yield (2.63 $t\,ha^{-1}$). Lupine intercropping at 40 cm inter-row spacing and two weeks after tef planting resulted in the highest land equivalent ratio (1.54), tef equivalent yield (2.45 $t\,ha^{-1}$), area time equivalent ratio (1.11), system productivity index (2.5), monetary advantage index (15206 birr ha^{-1}), net benefit (65109 birr ha^{-1}), and marginal rate of return (602%). Therefore, farmers in the northwest Ethiopian highlands should consider intercropping lupine two weeks after tef planting in-between two rows of tef as an effective intercropping system.

1. Introduction

Population increase in Ethiopia is surpassing agricultural food production [1]. This has resulted in a scarcity of farmland in Ethiopia's highlands [2]. Ethiopian farmers also lack sufficient land to plant both cereal and pulse crops in a sole cropping system [3]. Such farming practices do not generate enough food for the family in the Ethiopian highlands, where the average land holding is quite small [4]. The only approach to raise agricultural production is to increase yield per unit area [5].

Increasing land productivity per unit area by implementing land use is an interesting and advanced strategy [6]. Intercropping is an intensification of agricultural activities defined as growing two or more crops at the same space and time [7]. In terms of yield, intercropping outperforms monocropping by optimizing the use of all available resources that would otherwise be wasted by a monocrop [8, 9], improves soil fertility, increases yield stability, and raises returns [10]. The largest demands on environmental resources made by component crops are varied with planting and harvesting dates [11].

Tef is Ethiopia's most significant crop, accounting for 18.3% of total grain production [12] and over 66% of human nutrition [13]. However, tef productivity (1.66 $t\,ha^{-1}$) in the study area is still low [14], compared to the average national tef yield (1.75 $t\,ha^{-1}$) [12] and the maximum yields of 3.08 $t\,ha^{-1}$ and 3.40 $t\,ha^{-1}$ reported by Birhanu [15] and Wato [16], respectively.

Cereals have been intercropped with lupine [17]. Lupine is planted as a minor crop while cereals are the major crop. Farmers in the East Gojjam highlands are generally hampered by small farm sizes due to the high population density. Furthermore, due to land constraint, producing legumes as a monocropping system is difficult.

As a result, the key agricultural production strategies in the northwest Ethiopian highlands are innovative technology and sustainable crop development. An intercropping system is one technique to improve crop productivity [18]. Because of the wider 20 cm row spacing, which they consider as free ground, many farmers in East Gojjam are unwilling to sow tef in rows. Weed infestations could thrive in the open space. The extra space between rows makes intercropping legumes with tef easier. Rather than cultivating tef and lupine individually, the free land may be better utilized if the two were intercropped.

Selection of compatible species and timing of intercropping [19] as well as determining an optimal spatial row ratio are all important agronomic activities in intercropping. The intensity of interspecific competition for restricted growth resources between and among component crops is reduced when the best time for legumes is determined [20]. The appropriate spatial ratio had a significant impact on interspecies rivalry and yield production in maize-soybean relay strip intercropping [21]. Thus, there is a need to increase both the productivity of tef fields and the production of lupine. By relay intercropping lupine in tef fields, both of these goals might be met and achieved in practice. However, only a few research studies have been undertaken in the study area on the optimal timing of intercropping and planting density of lupine with tef to boost tef field's productivity.

Therefore, the objective of this study was to see if there was a way to boost tef field's productivity by maintaining optimal planting density and time of lupine as a relay crop.

2. Materials and Methods

2.1. Description of the Study Area. The experiment was conducted in 2016 and 2017 main cropping season at Enerata site in Gozamin district, East Gojjam zone, northwest Ethiopia highlands. The experimental site is located at latitude of 10°23′N and longitude of 37°44′E with the altitude of 2481 m.a.s.l. The study years map is presented in Figure 1. The weather data source was Debre Markos Metrological Station and based on 15 years (2003 to 2017) meteorological data; the average annual rainfall of the study areas was 1335 mm with mean minimum and maximum temperatures of 10.7°C and 23.2°C, respectively. Monthly average total rainfall and minimum and maximum temperatures of the study area for 15 years from 2003 to 2017 are presented in Figure 2. The total rainfall of the study years with a range of 0 to 271 mm per month is shown in Figure 2. The mean minimum and maximum temperatures of the study years were 11.2°C and 23.0°C, respectively (Figure 2). The rainfall distribution of the study years is uni-modal pattern and the main rainfall extends from the mid of June to October with peak in the mid of July to end of August (Figure 2).

To characterize the soil at the experimental site, a composite soil sample was taken before plowing by mixing samples collected at eight different spots along the two diagonal lines of the field at 0–30 cm depth with an auger. The composite soil sample was air dried and crushed to a sieve size of 2 mm before being analyzed for important physicochemical soil properties such as texture, pH, organic content, total nitrogen, available phosphorous, CEC, and exchangeable cations (Ca, Mg, K, and Na) using standard methods and procedures.

Debre Markos soil laboratory analyzed the collected soil samples. The pH of the soil was measured with a pH meter in a 1 : 2.5 soil: H_2O ratio, as described by Hazelton and Murphy [22]. The Bouyoucos hydrometer method was used to determine the texture of the soil [23]. The Walkley–Black wet digestion process was used to extract soil organic carbon [24]. Total N was calculated using the Kjeldahl digestion method of Havlin et al. [25]. The Olsen $NaHCO_3$ extraction method was used to extract available soil P [26]. The 1 N ammonium acetate extraction method, as described by Black, was used to determine cation exchange capacity [27], while an atomic absorption spectrophotometer was used to assess Ca and Mg [28]. Table 1 shows the findings of the soil laboratory analysis.

2.2. Experimental Materials Used for the Study. The tef variety "Quincho" [(974 × 196)-HT′-387 (RIL355)] was used as a test crop for the experiment. It was developed through combining of the high yielding with a good seed quality line. White lupine local variety was used for the present study.

2.3. Experimental Treatments, Design, and Procedures. The treatments were as follows: tef was planted at a 20 cm inter-row spacing, lupine was sown at 20 and 40 cm inter-row spacing (row ratio of 1 tef: 1 lupine and 2 tef: 1 lupine), and lupine intercropped three times (1, 2, and 3 weeks after tef planting). Randomized complete block design (RCBD) with 3 replications was used. Two sole cropping of tef and lupine were planted. The experimental field was plowed four times with an oxen-powered local plowing facility and then manually divided into blocks (replications) and plots according to the treatments and design. The net plot area was 2.4 m × 2 m (4.8 m^2) with a gross plot size of 4 m × 3 m (12 m^2). Adjacent plots and blocks were separated by 1.0 m and 0.5 m paths, respectively. Tef seeds in both cropping systems were drilled in rows, which were spaced apart with 20 cm, in early July 2016 at the recommended rate of 5 $kg\,ha^{-1}$. Lupine in the sole cropping system was planted at 40 cm inter-row and 10 cm intra-row spacing. Lupine in intercropping was planted as per treatments and design on the same date of tef sowing; 60 kg/ha N and 26 kg/ha P were applied for both cropping systems. All other agronomic management practices were done equally to all experimental plots as per their recommendations for tef in the study area.

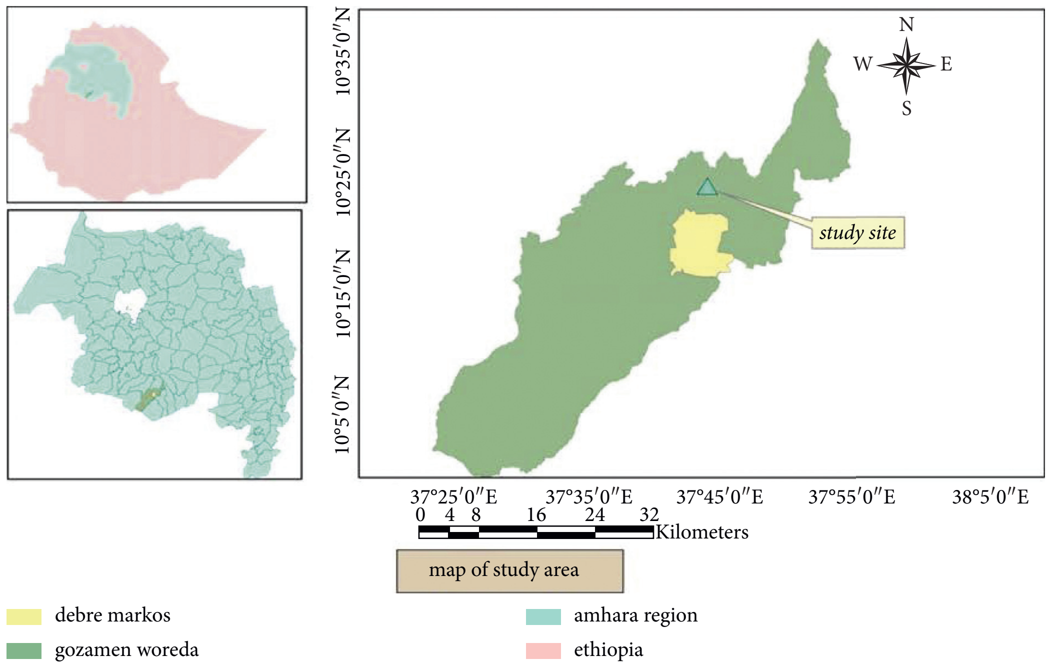

Figure 1: Location map of the study site in Enerata, East Gojjam zone, northwest Ethiopia.

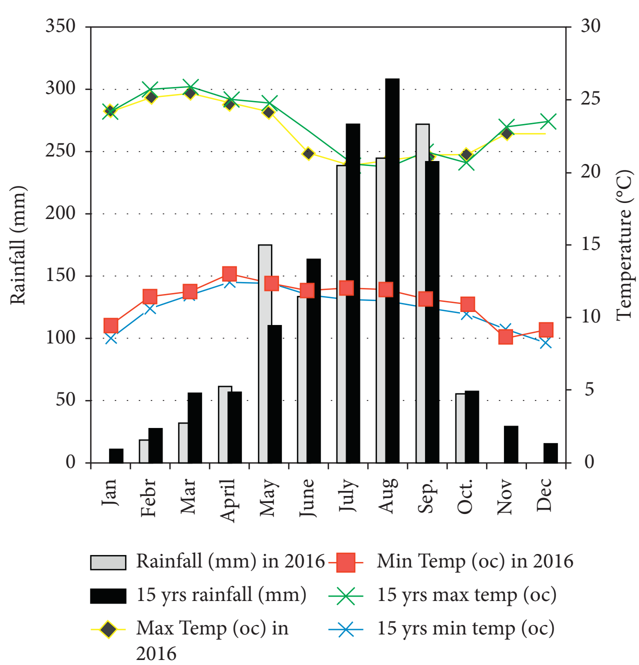

Figure 2: Monthly average rainfall and maximum and minimum temperatures of the study site for 15 years (2003–2017).

2.4. Crop Data Collection. Data on sole and intercropped tef growth and yield-related parameters were obtained on time using their standard methods and procedures. Panicle length and number of fertile tillers were measured on a plant basis in the net plot area of each plot by taking 10 randomly selected plants at physiologically mature growth stages, while biomass, grain, and straw yields were measured on a plot basis in the net plot area of each plot and converted to hectare basis (t/ha). After harvesting and proper drying with sunlight, the above-ground biomass yield of tef in each net plot area was weighed with a sensitive electrical balance. Following the completion of biomass yield data collection, the dried tef plants on plot basis thrashed manually in bags and grains were recovered and weighed with sensitive balance after wind winnowing and manual cleaning. Grain yield was adjusted to a moisture content of 12.5% before proceeding to statistical analysis. Straw yield was estimated as the difference of biomass and grain yields.

Agronomic parameters of lupine, such as the number of branches and pods per plant, were determined at physiological maturity from 10 randomly sampled lupine plants in the net plot area for the lupine crop. From ten randomly sampled plants in the net plot, grain and biomass yields (kg/ha) were determined. After harvesting the plant from the net plot area and sun-drying it until it reached a consistent dry weight, the total above-ground biomass of lupine was measured. Similarly, after separating the grain yield from the total biomass production, the grain yield of lupine was determined. The grain yield of lupine was dried, threshed, cleaned, adjusted to 10% moisture, weighted with sensitive balance, and converted into hectare basis.

2.5. Data Analysis. All crop data were subjected to analysis of variance (ANOVA) using SAS software version 9.4's General Linear Procedure [29]. The results of all agricultural variables over two years were subjected to the Bartlett homogeneity test, which was found to be unimportant, and thus a combined analysis of variance for the examined variables was undertaken across years. When the ANOVA results revealed a significant difference between treatments for a variable (s), the LSD test was used to further separate the treatments [30].

Table 1: Some important physicochemical properties of the experimental soils before plowing.

Soil and manure property	Soil analysis: Value	Soil analysis: Rating	Rating references
Particle distribution			
Sand (%)	32		
Silt (%)	25		
Clay (%)	43		
Soil texture class	Clay		
pH (H_2O)	5.1	Strong acidic	Hazelton and Murphy [22]
Total N (%)	0.09	Low	Havlin et al. [25]
Organic C (%)	1.27	Low	Charman and Roper (2007)
Avail. P (ppm)	6.85	Very low	Tekalign [26]
Exch. Mg (Meq/100 g)	0.84	Low	Metson [28]
Exch. Ca (Meq/100 g)	2.78	Low	Metson [28]
CEC	20.20	Moderate	Landon [27]

2.6. Analysis of Indices for Intercrop Efficiency

2.6.1. Competitive Ratio. The competitive ratio (CR) simply represents the ratio of individual land equivalent ratio of the component crops and takes into account the proportion of the crops in which they were sown:

$$CRT = \left(\frac{LERT}{LERL}\right) \times \left(\frac{ZTL}{ZLT}\right),$$
$$CRL = \left(\frac{LERL}{LERT}\right) \times \left(\frac{ZLT}{ZTL}\right), \quad (1)$$

where CRT and CRL are competitive ratio of tef and lupine, respectively, ZTL and ZLT are sown proportion of tef and lupine in intercropping, respectively, and LERT and LERL are land equivalent ratio of tef and lupine, respectively.

2.7. Actual Yield Loss. Actual yield loss (AYL) is the proportionate yield loss or gain of intercrops in contrast to the comparable sole crop. It is calculated as

$$AYL = AYTt + AYLl,$$
$$AYLt = \frac{\{YTL/ZTL\}}{\{(YT/ZTT) - 1\}}, \quad (2)$$
$$AYLl = \frac{\{YLT/ZLT\}}{\{(YL/ZLL) - 1\}},$$

where AYLt and AYLl are partial actual yield loss of tef and lupine, respectively.

ZTT and ZLL are sown proportion of tef and lupine in sole cropping, respectively, YTL and YLT are yield of tef and lupine in intercropping, respectively, and YT and YL are yield of tef and lupine in sole cropping, respectively.

2.8. Land Equivalent Ratio. Land equivalent ratio (LER) is the ratio of land required by a pure (mono) crop to produce the same yield as an intercrop. Its formula is

$$LER = LERT + LERL,$$
$$LERT = \left(\frac{YTL}{YT}\right), \quad (3)$$
$$LERL = \left(\frac{YLT}{YL}\right).$$

2.9. Area Time Equivalent Ratio. In terms of time spent on component crops in an intercropping system, the area-to-time equivalent ratio (ATER) provides a more realistic comparison of the performance advantages of intercropping over monoculture. Its formula is

$$ATER = \frac{\{(PLERT \times TT) + (PLERL \times TL)\}}{T}, \quad (4)$$

where PLERT and PLERL are partial land equivalent ratios of tef and lupine, respectively; TT is the growth period of tef in days; TL is the growth period of lupine in days, and T is the growth period of the crop in days.

2.10. Tef Equivalent Yield. Tef equivalent yield is the sum of tef yield in the intercrop system and the converted lupine yield and was compared with sole crop tef yield. Tef was the major crop; therefore, yield of the minor crop in the intercrop was converted to tef yield by multiplying the lupine yield with lupine/tef price ratio.

$$TEY = TY + LY\left(\frac{PL}{PT}\right), \quad (5)$$

where PT is the price of tef ton ha^{-1} and PL is the price of lupine ton ha^{-1}.

2.11. System Productivity Index. Another parameter to analyse intercropping is system productivity index (SPI), which regulates the yield of the minor (secondary) crop in terms of the main crop. Its formula is

$$SPI = \left(\frac{YT}{YL}\right) \times YTL + YLT. \quad (6)$$

2.12. Monetary Advantage Index. Monetary advantage index (MAI) finally was calculated since none of the above competition indices provides any information on the economic advantage of the intercropping system.

$$MAI = \frac{LER - 1}{LER} \times \text{value of combined intercrops}. \quad (7)$$

2.13. Partial Budget Analysis. Partially budget analysis procedures [31] were used to evaluate the economic feasibility of interventions on tef grain and straw yields, as well as lupine grain yield. The partial budget analysis was conducted using input market prices at the time of planting, while grain and straw yield market prices were obtained at harvest. Then, to achieve net yield of both crops, the suggested rate of 10% was reduced from all treatments. Gross field benefit was calculated by multiplying net yield with market price. Variable costs were added together and subtracted from gross benefits, resulting in a net benefit. The market prices of tef grain yield, straw yield, and lupine grain yield were birr 23.00, 3.50, and 13.00 per kg, respectively. The cost of labour per day was 80.00.

3. Results and Discussion

3.1. Weather Condition. The weather data source was Debre Markos Metrological Station, and based on 15 years (2003 to 2017) meteorological data, the average annual rainfall of the study areas was 1335 mm with mean minimum and maximum temperatures of 10.7°C and 23.2°C, respectively (Figure 2). Seyfu [32] indicated that tef is adapted to a broad range of Ethiopian agro-ecological environments. For optimal development, a minimum yearly rainfall of 700 mm and 300–500 mm during the growing season are necessary. Therefore, the amount of rainfall of the growing season was favorable for tef production.

Based on National Meteorological Agency data, the mean minimum and maximum temperatures of the study years were 11.2°C and 23.0°C, respectively (Figure 2). Seyfu [32] stated that tef favors cool production conditions (10–27°C). Hence, the temperature of the experimental site was favorable for tef production.

The ideal rainfall for lupine production is between 1100 and 2300 mm. Sweet lupins can thrive in temperatures ranging from 0°C to 30°C [33]. As a result, the trial site's meteorological conditions were suitable for lupine production.

3.2. Selected Physicochemical Properties of the Experimental Soil. The classification of the experimental soil is nitosol. The experimental soil's textural class was clay, with a pH of 5.1, based on the ratings of Hazelton and Murphy [22]; the soil pH was 5.1 rated as strongly acidic. Total nitrogen content was 0.09%, rated low based on the ratings of Havlin et al. [25] according to Walkley and Black [24]; the soil's organic carbon concentration was 1.27%, which is low. The available P content of the experimental soil was 6.85 ppm, which is very low based on the rating of Landon [27]. Magnesium and Ca were low, while (cation exchange capacity) CEC was moderate (Table 1).

Even though tef is produced across a wide range of soil, the soil of the experimental site is poor fertile. To improve its fertility, intercropping of cereals with legume is an important agronomic practice. Intercropping improves soil fertility through the addition of nitrogen by fixation and extraction from the component legume [34]. Lupine can grow and give reasonable yield in soils with relatively low fertility status [33]. The tape root system of lupine could exploit more water and nutrients from deeper soil layers than cereals [17].

3.3. Vegetative Growth, Grain Yield, and Yield-Related Parameters of Tef as Influenced by Plant Density and Time of Lupine Relay Cropping in Tef Fields. Intercropping treatments affected significantly ($P < 0.05$) plant height, effective tillers, and grain and straw yield of tef in both years and over combined years (Table 2). Inter-row spacing at 20 cm with early lupine intercropping produced the tallest (129.3 cm) tef plant height (Table 2). This could be due to increased competition for sunlight between lupine and tef. Girma et al. [35] recorded the maximum barley plant height for a spatial layout of 1 : 1 barley and faba bean intercropping. Increasing stem growth activity in response to increase sunlight competition could explain this. In contrast to our findings, Alemayehu et al. [36] discovered that delayed intercropping of common bean in maize resulted in longer maize height.

Wider inter-row spacing (40 cm) and delayed lupine intercropping produced the highest (6.3) average mean effective tef tillers per plant, while early lupine intercropping and narrow lupine inter-row spacing produced the lowest (20 cm) effective tef tillers per plant combined over two years (Table 2). Lupine intercropped in tef fields with wider spacing and delayed lupine resulted in less competition with tef and increased tef growth to bear more tef productive tillers. Narrow lupine spacing and early lupine intercropping, on the other hand, will severely compete with tef, making it difficult for tef to bear effective tillers. Girma et al. [35]; in accordance with the current report, found that the highest tiller number of barley is 7.6 in 2 : 1 barley to faba bean row ratio rather than a 1 : 1. This conclusion is supported by the findings of Awal et al. [37]. According to Joorabi et al. [38]; the maximum sorghum tiller number was observed from delayed intercropped of forage legumes in sorghum.

The highest tef yield (1.80 $t\,ha^{-1}$) was obtained from 40 cm inter-row spacing and delayed lupine intercropping, which is statistically comparable to the sole tef yield (1.77 $t\,ha^{-1}$) and the grain yield (1.76 $t\,ha^{-1}$) obtained from treatment 5, and the lowest grain yield (0.64 $t\,ha^{-1}$) was obtained from narrow inter-row spacing and early lupine with tef intercropping (Table 2). Increased lupine plant population (in closely spaced lupine plants) caused lupine shadowing, inter- and intraspecific competition of the component crops, and lower tef grain yield.

The increased growth and yield parameters were attributed to more efficient use of available resources (space,

Table 2: Effect of plant density and time of lupine relay cropping in tef (*Eragrostis tef*) on vegetative growth, yield, and yield components of tef in 2016 and 2017 main cropping seasons in northwest Ethiopian highlands.

			Plant height of tef (cm)			No. of effective tillers of tef			Grain yield of tef (t/ha)			Straw yield of tef (t/ha)		
T	IR (cm)	TI (weeks)	2016	2017	COY	2016	2017	COY	2016	2017	COY	2016	2017	COY
T1	**20**	**1**	128.5^{a}	130.0^{a}	129.3^{a}	1.8^{d}	2.1^{d}	2.0^{e}	0.76^{e}	0.84^{d}	0.80^{e}	3.38^{c}	3.37^{c}	3.37^{c}
T2		**2**	122.3^{ab}	112.3^{bc}	117.3^{b}	2.3^{cd}	2.4^{cd}	2.5^{d}	1.13^{d}	1.36^{c}	1.25^{d}	4.33^{b}	4.42^{b}	4.38^{b}
T3		**3**	109.9^{c}	104.0^{dc}	107.1^{c}	2.6^{c}	2.6^{c}	2.6^{d}	1.47^{c}	1.44^{bc}	1.45^{c}	4.79^{ab}	4.97^{ab}	4.88^{ab}
T4	**40**	**1**	111.0^{bc}	116.0^{b}	113.0^{bc}	4.7^{b}	4.4^{b}	4.6^{c}	1.57^{bc}	1.61^{ab}	1.60^{bc}	5.11^{a}	5.19^{a}	5.15^{a}
T5		**2**	106.1^{c}	112.8^{bc}	109.5^{bc}	5.2^{b}	5.7^{a}	5.4^{b}	1.74^{ab}	1.77^{a}	1.76^{a}	5.51^{a}	5.22^{a}	5.37^{a}
T6		**3**	105.1^{c}	100.1^{d}	103.1^{c}	6.5^{a}	6.1^{a}	6.3^{a}	1.85^{a}	1.74^{a}	1.80^{a}	5.48^{a}	5.51^{a}	5.50^{a}
Sole									1.80	1.74^{a}	1.77^{a}	5.4^{a}	4.83^{a}	4.80^{a}
	P value	**ns**	*	*	*	*	*	*	*	*	*	*	*	
	SE±	**5.3**	**4.6**	**4.0**	**0.34**	**0.23**	**0.24**	**0.11**	**0.08**	**0.07**	**0.33**	**0.35**	**0.23**	
	CV%	**6.6**	**5.8**	**4.2**	**10.6**	**12.1**	**8.8**	**8.7**	**7.1**	**6.7**	**12**	**8.9**	**7.2**	

Means within a column followed by the same letter(s) are not significantly different: ** = highly significant at $P < 0.01$; * = significant at $P < 0.05$; ns = nonsignificant at $P \geq 0.05$; T = treatment; IR = inter-row spacing of lupine; TI = time of lupine intercropping in weeks; COY = combined over years; SE± = standard error; CV = coefficient of variation.

nutrients, and light) compared to other intercropping treatments, which was attributed to the lupine's minimal shading effect, which improved photosynthesis efficiency. In line with our result, planting maize and dwarf beans at the same time in a ratio of 2 maize:1 bean might help maximize maize fields [39]. In finger millet black gram intercropping, grain yields of finger millet decreased from 92% to 60% of the respective sole crop yields as the black gram seeding proportion increased from 25% to 75% [11]. Similarly, Alemayehu et al. [36] found that intercropping typical in maize six weeks later resulted in the highest grain yield (4295 kg ha-1). In addition, Takele and Mohammed [40] discovered that intercropping haricot bean with maize reduced maize grain yield at higher haricot bean population.

Furthermore, tef equivalent yield (TEY) is the best tool to determine the overall productivity potential of an intercropping system. The maximum TEY (2.45 $t\,ha^{-1}$) was obtained from 40 cm inter-row spacing and intercropping of lupine 2 weeks after tef planting (Table 3). The difference in TEY between intercropping treatments was due to better use of natural (land, CO2, and light) and added (fertilizer and water) resources. This is in line with the results of Getachew et al. [4] who found that intercropping faba bean with tef resulted in a higher tef equivalent yield than sole crops.

Wider (40 intra-row spacing) and delayed lupine intercropping achieved the highest tef straw yield (5.50 $t\,ha^{-1}$) (Table 2). According to Matusso [41], intercropping maize and soybean increased maize straw yield significantly. Similarly, Getachew et al. [4] found that raising the proportion of faba bean in the mixture from 12.5 to 62.5% decreased the tef straw yield from 94% to 71%.

Table 3: Production efficiency of tef-lupine intercropping combined over years in 2016 and 2017 main cropping seasons in northwest Ethiopian highlands.

T	IR (cm)	TI (weeks)	LER	TEY (t ha-1)	ATER	SPI	MAI
T1	**20**	**1**	0.83^{c}	1.29^{c}	0.63^{d}	1.50^{d}	−433^{c}
T2		**2**	1.12^{b}	1.77^{b}	0.79^{c}	1.84^{c}	5069^{b}
T3		**3**	1.13^{b}	1.79^{b}	0.74^{c}	1.70^{c}	6891^{b}
T4	**40**	**1**	1.48^{a}	2.33^{a}	1.10^{a}	2.49^{a}	4944^{b}
T5		**2**	1.54^{a}	2.45^{a}	1.11^{a}	2.50^{a}	15206^{a}
T6		**3**	1.42^{a}	2.30^{a}	1.01^{b}	2.15^{b}	13492^{a}
	SE±	**0.05**	**0.09**	**0.04**	**0.08**	**1532**	

T = treatment; LER = land equivalent ratio; TEY = tef equivalent yield; ATER = area time equivalent ratio; SPI = system productivity index: MAI = monetary advantage index; IR = inter-row spacing of lupine; TI = time of lupine intercropping in weeks; SE ± = standard error.

3.4. Vegetative Growth, Grain Yield, and Yield-Related Parameters of Lupine as Influenced by Plant Density and Time of Lupine Relay Cropping in Tef Fields. Intercropping treatments significantly ($P < 0.05$) affected lupine height, pod plant^{-1}, and grain yield in both years and combined over years (Table 4). Early lupine intercropping and 20 cm lupine inter-row spacing produced the tallest lupine plant height (127.7 cm), while delayed intercropping and 40 cm spacing produced the shortest height (105.2 cm) (Table 4). This may be due to intraspecific competition, as plants become thinner and longer to compete for above-ground resources as plant density increases. Alemayehu et al. [36] found that delayed planting of common beans resulted in the shortest common bean plant height (94.95 cm), which is consistent with our findings. Megawer et al. [42] also found that in barley lupine intercropping, narrow inter-row spacing of lupine resulted in maximum plant height of lupine. This is because the competition, especially for light, has a direct impact.

Treatment 4 (early lupine intercropping and 40 cm lupine row spacing) produced the highest pods per plant (33.1), while treatment 3 (late lupine planting and narrow lupine spacing) produced the least (Table 4). In tef-lupine relay cropping, the number of pods per plant increased as the lupine planting density decreased. This decrease in number of pods per plant at higher density could be attributed to increased competition among plants for growth factors [43].

Combined over years, among the cropping systems, the highest lupine grain yield (2.63 $t\,ha^{-1}$) observed in sole lupine cropping system might be due to the optimum plant population in sole cropping and the absence of inter-species

Table 4: Effect of plant density and time of lupine relay cropping with tef (*Eragrostis tef*) on plant height, pods per lupine plant, and yield of lupine in 2016 and 2017 main cropping seasons in the highlands of northwestern Ethiopia.

			Plant height of lupine (cm)			No. of pods per lupine plant			Grain yield of lupine (t/ha)		
T	IR (cm)	TI (weeks)	2016	2017	COY	2016	2017	COY	2016	2017	COY
T1	**20**	**1**	129.7^{a}	126.7^{a}	127.7^{a}	24.6^{bc}	25.5^{bc}	25.1^{c}	0.98^{c}	1.01^{c}	0.99^{c}
T2		**2**	124.0^{ab}	125.0^{a}	124.5^{a}	21.0^{d}	22.3^{c}	21.1^{d}	1.04^{c}	1.08^{c}	1.06^{b}
T3		**3**	105.0^{c}	99.2^{b}	112.1^{b}	16.6^{e}	18.0^{d}	17.3^{e}	0.75^{d}	0.77^{d}	0.76^{d}
T4	**40**	**1**	111.0^{bc}	112.0^{ab}	111.5^{b}	32.6^{a}	33.6^{a}	33.1^{a}	1.46^{b}	1.48^{b}	1.47^{b}
T5		**2**	104.5^{c}	103.5^{b}	103.8^{c}	28.7^{b}	30.bb	29.5^{ab}	1.36^{b}	1.37^{b}	1.37^{b}
T6		**3**	102.1^{c}	107.6^{b}	102.3^{c}	27.0^{bc}	26.3^{b}	26.6^{bc}	0.99^{c}	1.03^{c}	1.00^{c}
Sole									2.62^{a}	2.65^{a}	2.63^{a}
	P value	ns	*	*	*	*	*	*	*	*	
	SE±	**7.9**	**7.3**	**7.1**	**1.4**	**1.5**	**1.3**	**0.06**	**0.07**	**0.05**	
	CV%	**8.6**	**8.1**	**8.4**	**7.1**	**7.4**	**6.6**	**6.4**	**7.0**	**5.7**	

Means within a column followed by the same letter(s) are not significantly different: * = significant at $P < 0.05$; ns = nonsignificant at $P \geq 0.05$; T = treatment; IR = inter-row spacing of lupine; TI = time of lupine intercropping in weeks; COY = combined over years; SE± = standard error; CV = coefficient of variation.

competition (Table 4). From the intercropping treatments, the highest lupine yield of 1.47 $t\,ha^{-1}$ was recorded from 40 cm inter-row spacing and early intercropping of lupine in tef fields, which is statistically at par with the yield obtained from treatment 5 (1.37 $t\,ha^{-1}$), while the lowest yield was recorded from delaying planting and wider inter-row spacing of lupine (Table 4). This is confirmed by Egbe [44], who found that the monocropping system produced the highest cowpea grain yield. The findings are also consistent with those of Oseni [45], who recorded 65% yield reductions in cowpea intercropped with sorghum in 1 : 2 row proportions.

3.5. Competition Indices. Intercropped tef had higher competitive ratios (CR) in all treatments, except treatment 1 (Table 5). When lupine was intercropped at 40 cm inter-row spacing and 3 weeks after tef was planted, the highest CR (2.96) value of tef was observed (Table 5). The findings of this result are consistent with those of Yu et al. [46]. Takele and Mohammed [40] also found that haricot bean intercropping in maize at a later time resulted in maize with the highest CR values. Furthermore, Ashenafi [47] discovered that the highest (0.72) and lowest (0.56) onion CR values were obtained in treatments with onion intercropped with rosemary at 20% and 80% population density, respectively.

Actual yield loss (AYL) of tef, lupine, and total in 20 cm inter-row spacing was negative at all dates of lupine intercropping, indicating the disadvantage of intercropping over monoculture, while positive actual yield loss (1.13, 1.15, and 1.08) was obtained from treatments 4, 5, and 6 based on two years averaged data (Table 5). The highest actual yield loss (1.13) was caused by 40 cm inter-row spacing and intercropping of lupine two weeks after tef planted (Table 5). AYL provides more detailed information about competition between and within component crops than the other indices [19]. Intercropping is preferable to pure stands because it makes greater use of growth resources and reduces rivalry between the tef and lupine crops. Positive values of AYL were recorded in onion rosemary intercropping at a population density of 20%, 9 [47]. Similar results have been reported by Aasim et al. [48].

Table 5: Competitive ratio and actual yield loss of tef and lupine in tef-lupine intercropping system combined over years in 2016 and 2017 main cropping seasons in northwest Ethiopian highlands.

T	IR (cm)	TI (weeks)	CRT	CRL	AYLt	AYLl	AYLtt
T1	**20**	**1**	0.84^{e}	1.92^{a}	−0.54^{d}	−0.64^{d}	−1.18^{d}
T2		**2**	1.02^{b}	0.98^{c}	−0.28^{c}	−0.61^{d}	−0.89^{c}
T3		**3**	1.40^{c}	0.80^{c}	−0.17^{c}	−0.72^{e}	−0.89^{c}
T4	**40**	**1**	1.42^{c}	1.41^{b}	0.51^{b}	0.62^{a}	1.13^{a}
T5		**2**	1.84^{b}	1.03^{c}	0.63^{a}	0.50^{b}	1.15^{a}
T6		**3**	2.96^{a}	0.92^{c}	0.58^{a}	0.50^{c}	1.08^{b}
	SE ±	0.19	0.11	0.11	0.04	0.06	

T = treatment; CR = competitive ratio of tef and lupine in intercropping; AYL = actual yield loss of tef and lupine in intercropping; IR = inter-row spacing of lupine; TI = time of lupine intercropping in weeks; COS = combined over years; SE ± = standard error.

Intercropping of lupine at 40 cm inter-row spacing and 2 weeks after tef planting resulted in the highest MAI of 15206 ETB ha^{-1}, while early intercropping of lupine at 20 cm inter-row spacing produced the lowest MAI of -433 ETB ha^{-1} (Table 3). MAI is one of the economic profitability indices used to determine whether an intercropping system is more profitable or productive than monocropping [49]. The results were in agreement with the finding of Islam et al. [50] who reported that higher MAI values were found in turmeric sesame intercropping systems compared to sole cropping system.

In this study, LER is more than one in all intercropping treatments, except treatment 1 (Table 3). LER does not consider the duration of the crops in the field and it is based on the harvested products and not on desired yield proportion of the component crops. With the highest LER of 1.54, sole cropping will take 0.54 more units of land to produce the same yield as intercropped (Table 3). The yield advantage may be attributed to the intercropped crop's efficient use of available resources compared to monocropped ones. Similar result was reported by Alemayehu et al. [36]. This result contrasted with the findings of Peksen and Gulumser [39], who found that planting common bean and maize at the same time resulted in higher LER values than delayed common bean intercropping.

Table 6: Economic profitability of tef-lupine intercropping combined over years as influenced by plant density and relay intercropping of white lupine with tef in 2016 and 2017 main cropping seasons in northwest Ethiopian highlands.

Treatment	IR (cm)	TL (weeks)	Adj. tef GY (t/ha)	Adj. tef SY (t/ha)	Adj. lupine GY (t/ha)	GB (birr/ha)	VB (birr/ha)	NB (birr/ha)	MRR (%)
	Sole tef		1.6	4.32		51920	1006	50914	1.6
T_4	40	7	1.44	4.63	1.32	66485	3846	62639	413
T_5		14	1.58	4.83	1.24	69365	4256	**65109**	**602**
T_6		21	1.62	4.93	0.9	66215	4946	61269	
T_1	20	7	0.71	3.03	0.89	38505	5887	32618	
T_2		14	1.13	3.9	0.94	51860	7996	43864	533
T_3		21	1.31	4.39	0.69	54465	8982	45483	164

IR = inter-row spacing of lupine; TL = time of lupine intercropping in weeks; GY = grain yield, SY = straw yield price; GB = gross field benefit; VB = variable cost; NB = net benefit; MRR = marginal rate of return; EB kg^{-1} of tef grain yield, straw yield, and lupine grain yield were 23.00, 3.50, and 13.00. Labour cost per day^{-1} was 80.00.

Area time equivalent ratio values were found greater than unity in treatments 4, 5, and 6 and showed 2–11% yield advantage as compared to sole cropping (Table 3). In our research, LER values were higher than ATER values (Table 3), suggesting that resource use was overestimated. Two weeks of lupine intercropping after tef planting at 40 cm inter-row spacing resulted in the highest yield advantage (1.11) (Table 3). In conformity with our result, Aasim (2008) found higher ATER values. Khan et al. [51] also reported that maize 100% + garden pea (36%) generated the highest ATER value (1.28) compared to other intercropping systems.

The highest SPI (2.50) was obtained from delayed intercropping and wider lupine inter-row spacing (Table 3). The system productivity index established the combinations that best exploited growth resources while maintaining a consistent yield performance [45]. Khan et al. [51] and Cui et al. [21] reported similar findings. In contrast to our findings, Takele and Mohammed [40] observed that intercropping of haricot bean at the same time with maize produced the highest SPI than delayed planting.

3.6. Partial Budget Analysis. From the final tef and lupine grain yield as well as tef straw yield, the gross yield of each treatment was obtained. Then, the recommended level of 10% was reduced from all treatments to obtain net grain yield and straw yield. Net yield was multiplied by the market price to obtain gross field benefit. All variable costs were calculated based on the current price as per the information obtained from local markets. Variable costs were summed up and subtracted from gross benefits, which were taken as net benefit (Table 6). The highest net benefit (65109 birr ha^{-1}) and marginal rate of return (602%) were obtained from 40 cm inter-row spacing and intercropping of lupine 2 weeks after tef planting (Table 6), implying that for every birr invested in tef production, the producer will receive birr 6.02 after recovering his investment CIMMYT [31]. This represents an increase in net return of at least 1 birr for every one birr invested. Therefore, 40 cm inter-row spacing and intercropping of lupine 2 weeks after tef planting had the highest tef equivalent yield of 2.45 $t\,ha^{-1}$ (Table 3) and thus had higher net benefit (65109 birr ha^{-1}) and acceptable MRR (602%) can be recommended for farmers in the area.

Therefore, in the study area, the productivity of tef fields per unit area increased through intercropping of lupine at 40 cm inter-row spacing and 2 weeks after tef planting.

4. Conclusion

The current study found that tef-lupine relay cropping systems had a significant effect on both crops' growth parameters, yield, and yield components. Over combined years, 40 cm inter-row spacing and delayed lupine intercropping (3 weeks after tef planting) produced the highest tef grain yield (1.80 $t\,ha^{-1}$). Similarly, lupine sole cropping produced the highest lupine grain yield (2.63 $t\,ha^{-1}$).

The results of this study showed that by relay cropping, it is possible to increase lupine yield without reducing tef yield in both years. Furthermore, higher land equivalent ratio (1.54), tef equivalent yield (2.45 $t\,ha^{-1}$), area time equivalent ratio (1.11), actual yield loss (1.15), system productivity index (2.5), monetary advantage index (15206.00 birr ha^{-1}), net benefit (65109 birr ha^{-1}), and marginal rate of return (602%) were recorded from intercropping of lupine at 40 cm inter-row spacing and 2 weeks after tef planting.

In conclusion, farmers in the northwest Ethiopian highlands should use intercropping lupine two weeks after tef planting in-between two rows of tef as an effective intercropping system.

To confirm the findings, further research is needed to test more legume species that are consistent with the tef intercrop system across seasons and locations.

Data Availability

The data that support the findings of this study are available on request from the corresponding author.

Disclosure

No potential conflicts of interest were reported by the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Yirsaw Hunegnaw, the corresponding author, was responsible for all aspects of the study, including data collection, data analysis, and manuscript writing. All authors contributed to the improvement and finalization of the text, as well as reading and approval of the final edition.

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