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Optimizing resources for sustainable maize production under different intercrop association in eastern sub Himalayan region of India

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Intercropping is a sustainable agricultural approach that plays a crucial role in improving land use efficiency, enhancing soil fertility and boosting overall crop productivity. In the eastern sub Himalayan region of West Bengal, India, this practice holds significant promise for transforming traditional farming by optimizing yield per unit area while promoting environmental sustainability. Maize (*Zea mays* L.), a highly adaptable crop that serves as a staple food and animal feed, can benefit substantially from intercropping with legumes and non-legumes. However, systematic evaluations of maize-based intercropping systems in this region remain limited. This study was conducted to assess the comparative performance of four maize based intercropping systems namely maize-mustard, maize-lentil, maize-wheat and maize-pea conducted during the rabi seasons of 2021–22 and 2023–24. The hypothesis posited that intercropping with legumes would significantly enhance maize productivity. The experiment followed a Randomized Block Design (RBD) with four replications and key parameters such as growth traits, yield components, weed control, nutrient uptake, changes in soil chemical properties and economic outcomes were measured. Sole maize plots recorded superior growth and yield attributes, producing the highest grain yields. However, the maize + pea intercropping system markedly outperformed in terms of overall system productivity, increasing yield by 62.31 and 68.84% over sole maize in the first and second years, respectively. Legume-based systems not only contributed to better weed suppression but also enhanced soil fertility. The economic analysis revealed that the maize + pea system delivered the highest additional net returns of ₹92,441 and ₹1,12,775 ha^{-1} in the first and second years compared to sole maize. The results clearly demonstrate the advantages of intercropping maize, especially with pea, under rabi conditions in the eastern sub-Himalayan region. This strategy significantly boosts productivity, improves resource use efficiency and maximizes economic benefits. These findings provide critical insights into sustainable crop management and can serve as a model for other regions with similar agro-ecological conditions. The study strongly advocates for the integration of legumes in maize intercropping systems, highlighting their potential to address the twin challenges of food security and environmental sustainability.

KEYWORDS
maize, intercrop, pulse, cereals, weed control, sustainability

1 Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as a staple food for millions and playing a crucial role in livestock feed and industrial raw materials (Giller et al., 2009). In India, maize is cultivated over an area of 10.04 million hectares, producing 33.62 million tonnes with an average yield of 3.35 t ha^{-1}. In Eastern Sub Himalayan region, particularly in West Bengal, the maize growing area is expanding continuously, currently covering 0.37 million hectares with a productivity of 7.2 t ha^{-1} (Ministry of Agriculture and Farmers Welfare, Department of Agriculture, cooperation and farmer's welfare, Government of India, 2022). This highlights the promising potential of the region for maize cultivation. Its production faces numerous challenges, including soil nutrient depletion, increasing input costs, climate variability and environmental degradation due to unsustainable farming practices (Fischer et al., 2014). These challenges necessitate innovative and sustainable strategies to enhance productivity while minimizing environmental impacts (Lal, 2004). Sustainable agriculture seeks to balance productivity with environmental conservation, resource efficiency and economic viability (Tilman et al., 2011). Inter-cropping can be defined as the simultaneous cultivation of two or more crop species on the same piece of land, has emerged as a sustainable approach to address these issues. This practice leverages the complementary interactions between different crops to optimize resource use, improve soil health and enhance system resilience (Barman et al., 2022; Bybee-Finley and Ryan, 2018). Intercropping systems can increase land productivity through more efficient utilization of sunlight, water and nutrients, while also contributing to pest and weed management (Yu et al., 2024; Morris and Garrity, 1993). Additionally, such systems promote biodiversity and ecological balance, making them a vital component of sustainable agricultural practices. In association with suitable companion crops (legume, oilseed or cereal), maize can harness the benefits from synergistic effects that improve yield stability and reduce reliance on synthetic inputs (Zhang et al., 2024).

For instance, maize-legume intercropping systems are widely recognized for their ability to enhance nitrogen use efficiency due to the nitrogen-fixing capacity of legumes (Li et al., 2024). Similarly, intercropping maize with deep-rooted crops can enhance soil structure and water retention, making the system more resilient to drought conditions and can diversify farm outputs, improve economic returns and stabilize farmers' incomes (Nasar et al., 2023). Relay intercropping of maize with soybean resulted in a mutually beneficial yield advantage, while strip intercropping of maize with peanut led to a trade-off in yield benefits (Fu et al., 2023). Intercropping maize with cowpea in a 1:1 row ratio led to a notable 13.6% increase in overall system yield (Begam et al., 2024).

The success of intercropping systems in the eastern Sub-Himalayan region of India depends on multiple factors, such as crop compatibility, planting arrangements, agronomic management, and local environmental conditions (Bybee-Finley and Ryan, 2018). Recent advancements in research have explored optimizing intercrop combinations, planting densities, and nutrient management strategies to maximize benefits while minimizing trade-offs, providing context-specific recommendations for sustainable intensification. Studies have explored various intercrop combinations, planting densities, and nutrient management strategies to develop context specific recommendations for farmers (Huss et al., 2022). Despite its potential, the adoption of intercropping remains limited in many regions due to a lack of awareness, technical knowledge and policy support (Giller et al., 2009). Therefore, there is a growing need for interdisciplinary research to address these barriers and refine intercropping systems for different agroecological zones of the Sub-Himalayan region of India (Tilman et al., 2011). Such research can play a pivotal role in transforming maize production into a more sustainable and resource efficient system, contributing to global food security and environmental conservation (Brooker et al., 2015). Despite of numerous advantages of intercropping, there is still a considerable gap in identifying the most important intercrops for different agro ecological zones and season to ensure optimal resource utilization and sustainable maize production.

This research gaps offer an opportunity to optimize resource use in sustainable maize production by evaluating the agronomic, environmental and economic benefits of intercropping maize with legumes and non-legumes. We hypothesize that maize intercropping with legumes results in higher land use efficiency, economic return, enhance soil fertility, natural weed management and system sustainability over time than sole maize. With nearly 66% of the global population currently malnourished (WHO, 2024), and an estimated 60% of cultivated soils suffering from growth limiting problems (Cakmak, 2002), the necessity for sustainable agricultural practices that prioritize soil health alongside yield quality is starkly underscored. Concentrating on maize cultivation in the state of West Bengal, India, present study seeks to empirically examine the effects of intercropping with both legume and non-legume, highlighting the associated challenges and opportunities for advancing sustainable agriculture in an evolving global context. The objectives of the present experiment are threefold: (i) to find out best suited intercrops in rabi maize, (ii) to evaluate the smothering effect on weeds and (iii) to evaluate the economics of maize based intercropping system. This research significantly contributes to the field of sustainable agriculture, particularly in the context of field crops research and practice. The study underscores the benefits of integrating legumes with maize in intercropping systems, paving the way for innovative agricultural practices that can meet the dual challenges of food security and environmental sustainability.

The research further explores the challenges and opportunities for the broader adoption of intercropping and provides actionable insights for farmers, researchers and policymakers to promote sustainable intensification in maize-based systems.

2 Methods

2.1 Description of the experimental field

The present study aimed to evaluate the performance of different intercropping systems involving five crops maize, mustard, lentil, wheat and pea under the agro-climatic conditions of the sub-Himalayan plains of West Bengal. The experiment was conducted at the

Instructional Farm of Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar at an elevation of 43 meters above mean sea level (MSL) during the rabi seasons of 2021–22 and 2022–23. The experimental site situated in a subtropical humid climate characterized by moderate to cool winters and hot humid summers. The region receives significant annual rainfall predominantly during the monsoon season (June to September) with occasional winter showers. The average annual rainfall of the area is around 3,000 mm with temperatures ranging from a maximum of 35°C in the summer months to a minimum of 7°C during the winter season. During the period of research, rainfall, maximum and minimum temperature, maximum and minimum relative humidity and sunshine (hours) were monitored and presented in Figure 1. The soil type of the experimental field is alluvial characterized by sandy loam texture with good drainage conditions. Prior to the start of the experiment and after harvesting of crop, composite soil samples were collected from depth (0–15 cm) from multiple locations across the field. These samples were thoroughly mixed, air-dried ground and sieved through a 2 mm mesh to determine various chemical properties. The soil was analyzed for pH, organic carbon content, available nitrogen, phosphorus and potassium using standard protocol mentioned in Table 1. The results indicated that the soil was slightly acidic (pH 5.62 and 5.60 during Y-I (First year) and Y-II (Second year), respectively) with a moderate level of organic carbon (0.64 and 0.66% respectively) and was classified as sandy loam (clay 15%, silt 22%, and sand 63%). Soil available nitrogen (141.5 and 145.3 kg ha^{-1}), phosphorus (28.3 and 29.5 kg ha^{-1}) and potassium (152.5 and 154.0 kg ha^{-1}) was observed, respectively during both the year of experiment.

2.2 Experimental design and treatments

The experiment was laid out in a Randomized Block Design (RBD) with four replications to ensure reliability and statistical accuracy. A total of five treatments were evaluated consisting of four intercropping combinations. The main crop for the intercropping experiment was maize (var. DKC-9081) while mustard (var. B-9), lentil (var. L-4717), wheat (var. DBW-187) and pea (var. PUJA GS-10) were chosen as intercrops. Each treatment plot was carefully designed to maintain a planting pattern that optimized intercropping performance. Maize rows were spaced 60 cm apart with one row of intercrop placed between each maize row. The plant to plant spacing for lentil, pea and wheat was maintained at 10 cm while for mustard it was set at 15 cm.

Treatment details of the experiment are mentioned below, T_1 = Maize + Lentil; T_2 = Maize + Mustard; T_3 = Maize + Wheat; T_4 = Maize + Pea; and T_5 = Sole maize and all component crops are grown as sole crop in individual plot, for comparison of growth and yield parameters such as mustard, lentil, wheat and pea (Figure 2 and Tables 2, 3).

2.3 Fertilizer management

Fertilizer management in the intercropping system was based on the recommended doses of fertilizers (RDF) for maize (var. DKC-9081) and component intercrops, adjusted for plant populations. Maize received 100% RDF (150 kg N, 75 kg P_2O_5,

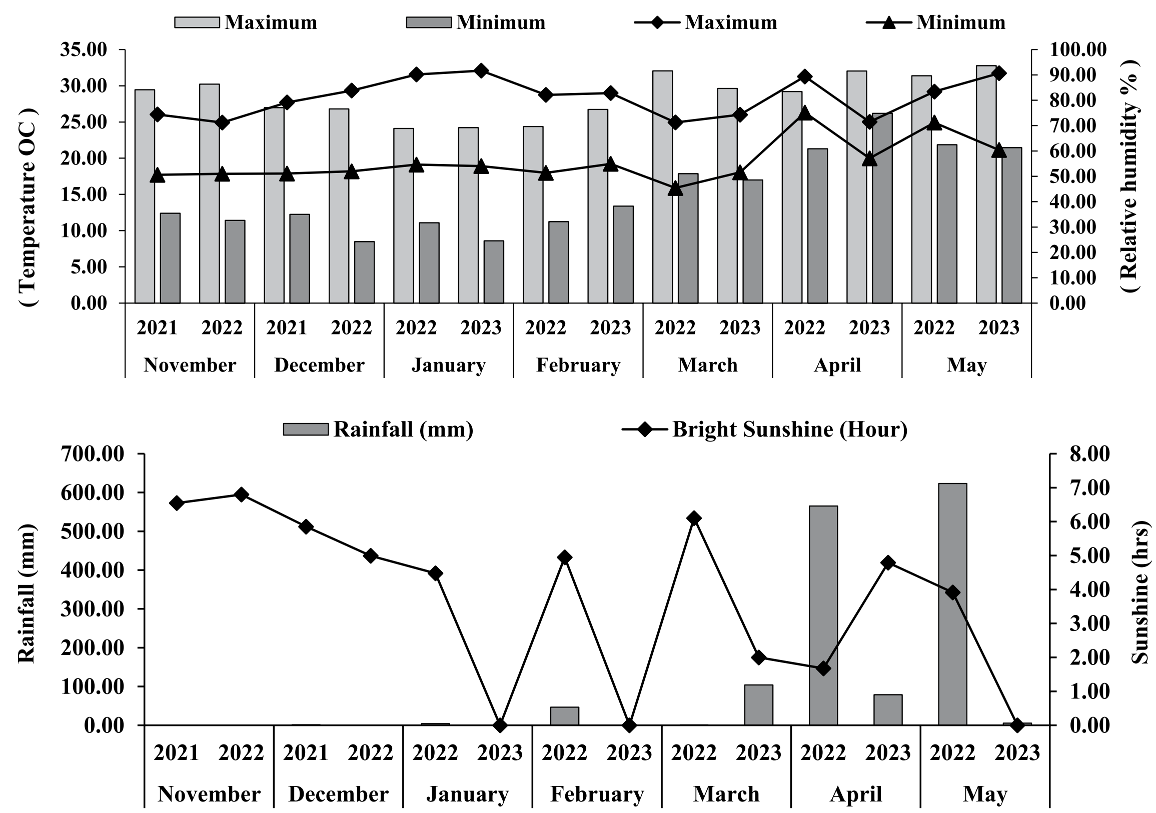

FIGURE 1
Meteorological observations recorded during the period of experimentation.

TABLE 1 Methodology followed for analysis of physical and chemical properties of soil.

Particulars	Method employed
Sand, silt and clay	International pipette method (Khanna and Yadav, 1979)
pH	pH meter (Baruah and Borthakur, 1997)
Organic carbon (%)	Rapid titration method (Walkley and Black, 1934)
Available nitrogen (kg ha^{-1})	Modified Macro Kjeldahl method (Jackson, 1967)
Available phosphorus (kg ha^{-1})	Bray's No. I Method (Jackson, 1967)
Available potassium (kg ha^{-1})	Flame photometer method (Jackson, 1967)

75 kg K_2O ha^{-1}) to ensure optimal growth. Fertilizer requirements for intercrops-mustard were proportionally adjusted based on reduced plant populations compared to pure stands. For mustard 22.5:22.5:22.5 and for wheat 28.13:22.5:15 kg/ha of NPK were applied as basal, while for legume intercrops, pea and lentil NPK were added @15:25:25 and 10:20:20 kg/ha. Urea, single superphosphate and muriate of potash was used as a source of nitrogen, phosphorus and potassium, respectively.

Fertilizer application followed a two-stage strategy. For maize, 50% of nitrogen (75 kg ha^{-1}) and the full phosphorus and potassium doses were applied basally at sowing, with the remaining nitrogen split into two top dressings at the V_4 and V_8 growth stages. Intercrops received adjusted basal doses of nitrogen, phosphorus and potassium. Additional nitrogen was applied to non-legume intercrops (wheat: 28.13 kg ha^{-1}, mustard: 22.5 kg ha^{-1}) during active vegetative growth, while legumes (lentil and pea) did not receive top-dressed nitrogen.

2.4 Crop geometry followed

The seed rate and spacing were optimized for maize (var. DKC-9081) and intercrops in the intercropping system. Maize was sown at a constant population of 66,667 plants ha^{-1} with a row spacing of 60 cm and intra-row spacing of 30 cm. Intercrops (mustard, lentil, wheat and pea) were sown with adjusted seed rates and spacings to accommodate reduced plant populations. For mustard, spacing adjusted from 45 cm × 15 cm to 60 cm × 15 cm, reducing plant density by 25%; seed rate reduced from 5 kg to 3.75 kg ha^{-1}. In case of lentil and Pea, spacing changed from 30 cm × 10 cm to 60 cm × 10 cm, reducing plant density by 50%; seed rates reduced from 40 to 20 kg ha^{-1} (lentil) and 75 to 37.5 kg ha^{-1} (pea). For wheat, spacing modified from 22.5 cm × 10 cm to 60 cm × 10 cm, reducing plant density by 62.5%; seed rate reduced from 100 to 37.5 kg ha^{-1}. All intercrops were planted between maize rows with fixed spacing (60 cm). These adjustments ensured optimal population densities and resource utilization in the intercropping system.

2.5 Statistical analysis

All the data recorded during the course of investigation were subjected to statistical analysis with the help analysis of variance (ANOVA) technique for randomized block design using statistical software R-4.3.3 for comparing critical difference and standard error of mean. The results are presented at 5% level of significance ($p = 0.05$). Duncan multiple range test was done to compare the critical values for comparisons between means. The Duncan multiple range test enhances the reliability and clarity of your statistical analysis by providing detailed and accurate comparisons among multiple treatment groups.

2.6 Intercropping indices

2.6.1 Maize equivalent yield (MEY)

Maize Equivalent Yield (MEY) is a measure used to compare the productivity of different intercropping systems by converting the yield of all crops in an intercropping system to an equivalent yield of maize considering the market prices of maize and other crops. It provides a common basis for evaluating the performance of various cropping systems and helps in assessing the efficiency of resource use. Willey (1979) MEY was calculated by considering the prices of the two crops using the following formula.

$$\text{MEY} = \text{Maize yield} + \frac{\text{Yield of intercrop}\left(\text{t ha}^{-1}\right) \times \text{Price of intercrop}\left(₹\ \text{t}^{-1}\right)}{\text{Price of maize}\left(₹\ \text{t}^{-1}\right)}$$

2.6.2 Land equivalent ratio (LER)

Land equivalent ratio to evaluate resource utilization in intercropping compared to sole cropping, the method proposed by Mead and Willey (1980) was applied, using the suggested formula.

$$\text{LER} = \frac{\text{Yab}}{\text{Yaa}} + \frac{\text{Yba}}{\text{Ybb}}$$

Where,
'Yaa' denotes 'A' crop yield in pure stand cropping.
'Ybb' denotes 'B' crop yield in pure stand cropping.
'Yab' denotes 'A' crop yield in intercropping.
'Yba' denotes 'B' crop yield in intercrops.

2.6.3 Relative yield total (RYT)

It is important to determine which crop combination produces a higher yield. The yield advantage is measured not only on a per-unit area basis but also per-unit population, as estimated by the relative yield total a concept introduced by De Wit and Van den Bergh (1965). This relative yield total is considered the most important index of biological advantage in intercropping systems.

$$\text{RYT} = \frac{\text{Yab} + \text{Yba}}{\text{Yaa} + \text{Ybb}}$$

Where,
'Yaa' denotes 'A' crop yield in pure stand cropping.
'Ybb' denotes 'B' crop yield in pure stand cropping.
'Yab' denotes 'A' crop yield in intercropping.
'Yba' denotes 'B' crop yield in intercrops.

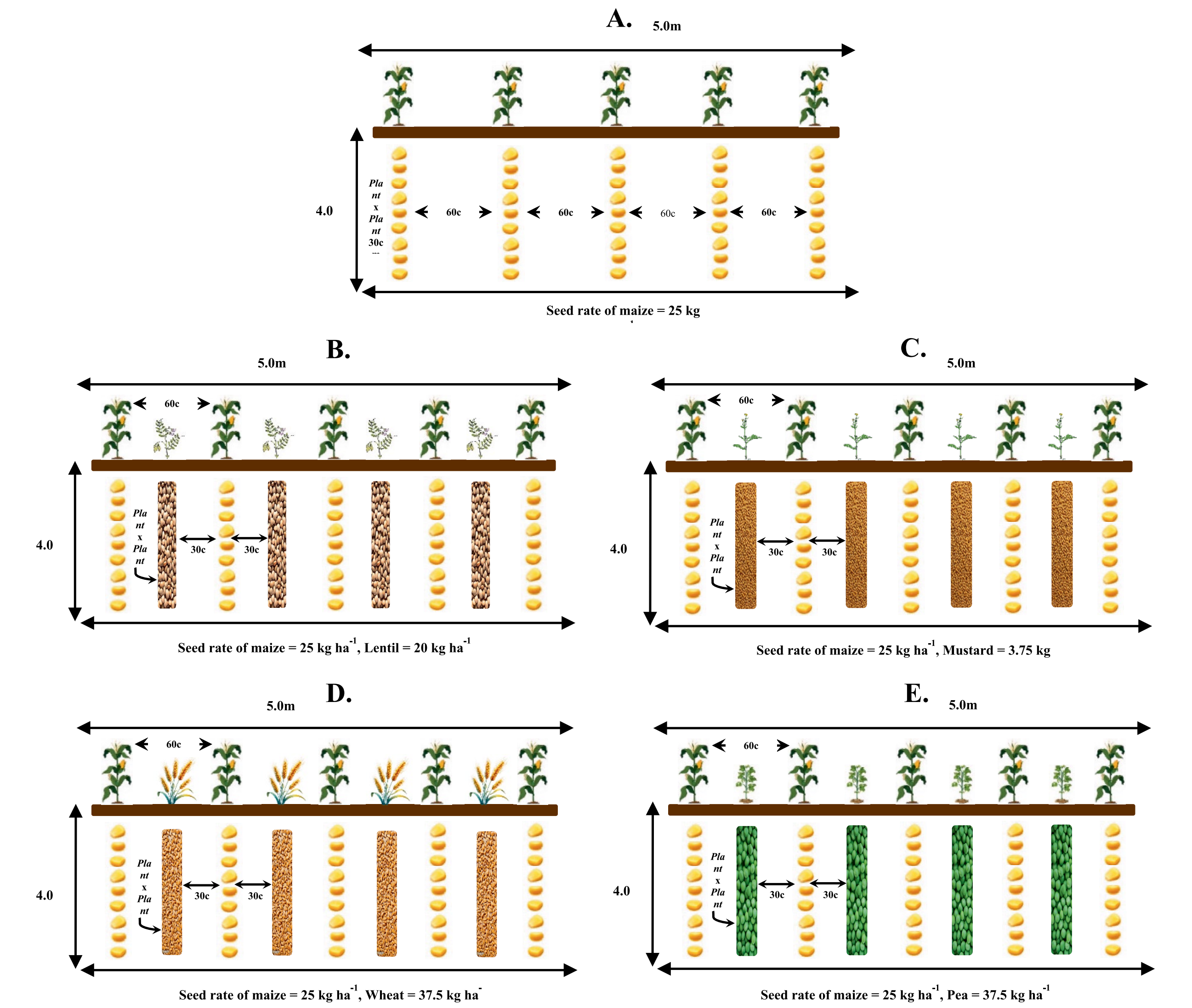

FIGURE 2
Layout of treatments and plot dimensions—**(A)** sole maize, **(B)** maize + lentil, **(C)** maize + mustard, **(D)** maize + wheat, **(E)** maize + pea.

TABLE 2 Year wise sowing and harvesting dates of sole maize and intercrops.

Crop	Sowing date		Harvesting date	
	Year-I	Year-II	Year-I	Year-II
Maize	24.11.2021	21.11.2023	20.04.2022	21.04.2024
Mustard	24.11.2021	21.11.2023	28.02.2022	25.02.2024
Wheat	24.11.2021	21.11.2023	19.03.2022	20.03.2024
Lentil	24.11.2021	21.11.2023	14.03.2022	15.03.2024
Pea	24.11.2021	21.11.2023	08.02.2022 and 23.02.2022	04.02.2024 and 20.02.2024

TABLE 3 Minimum support price of maize and intercrops (₹ t^{-1}) (Source: Ministry of agriculture and farmer welfare, Govt. of India).

Year	Maize	Wheat	Lentil	Mustard	Pea
Year-I	19,620	21,250	60,000	54,500	25,000
Year-II	20,900	22,750	64,250	56,500	29,000

2.6.4 Area time equivalent ratio (ATER)

Area Time Equivalent Ratio (ATER) introduced by Hiebsch (1980), addresses the limitation of the Land Equivalent Ratio (LER) by incorporating both the area and time required for ratio intercropping systems; an ATER > 1 indicates greater overall productivity, ATER = 1 signifies equal efficiency to sole cropping, and

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ATER < 1 suggests lower efficiency when both area and time are considered. Calculate by using the following formula.

$$\text{ATER} = \frac{(\text{RYa} \times \text{ta}) + (\text{RYb} \times \text{tb})}{\text{T}}$$

Where,

'RY' = relative yield of intercrop;

't' denotes duration (days) for intercrop;

'T' denotes duration of intercropping system (days); 'a' denotes maize; 'b' denotes intercrop.

2.6.5 Monetary advantage index (MAI)

Monetary Advantage Index (MAI) introduced by McGilchrist (1965), evaluates the financial benefits of intercropping by comparing the monetary value of produce with sole cropping; positive MAI indicates higher net returns from intercropping, zero suggests no financial difference, and a negative MAI reflects lower returns, with values often expressed in thousands depending on the scale of analysis. Calculate by using the following formula.

$$\text{MAI} = \frac{\text{LER} - 1}{\text{LER}} \times \text{value of combined intercrops}$$

Where,

LER is land equivalent ratio.

2.7 Weed density, biomass and smothering efficiency

In intercropped treatments, no weeding was performed during the growing season. Instead, weed suppression relied on natural competition and canopy shading by the intercrops, allowing assessment of the weed suppressing ability of leguminous and non-leguminous species without external intervention. While in the sole maize treatment a dual approach was employed to compare weed pressure and crop yield under weed control and no weed control conditions. Five randomly placed 1 m^2 quadrates per plot were left unweeded to simulate natural weed growth, while the rest of the plot underwent manual weeding at critical stages. This setup enabled comparison of weed dynamics and crop performance between intercropped and sole maize systems under both weeded and unweeded conditions.

Weed data were collected at 20, 40, 60, and 80 days after sowing (DAS), and at harvest, by counting the number of weeds in each quadrate. Densities were averaged and expressed as weeds per square meter. Weeds were also oven dried at 65°C to determine dry biomass, expressed in grams per square meter. Weed smothering efficiency (WSE) was determined using the following formula and express in percentage.

$$\text{WSE} = \frac{\text{Mdw} - \text{Idw}}{\text{Mdw}} \times 100$$

Where,

Mdw-Mean dry weight of weeds in pure crop plot (g m^{-2}), and

Idw-Mean dry weight of weeds in intercropped plot (g m^{-2}).

3 Results

3.1 Effect on growth attributes

The influence of leguminous and non-leguminous intercropping systems on growth attributes of maize (*Zea mays* L.) is presented in Tables 4, 5.

It was clearly seen that sole maize (T_5) consistently showed the tallest plants at all stages (60–120 DAS and harvest) except 20 and 40 DAS across both years which was statistically at par with maize + pea (T_4), while maize + mustard (T_2) recorded the shortest height. At harvest, sole maize achieved maximum heights of 309.54 cm (y-I) and 320.04 cm (y-II), while maize + mustard had the least of 249.46 cm (Y-I) and 280.98 cm (Y-II).

Dry matter accumulation (DMA) is an important factor as it has direct co-relation with grain yield of maize. Build-up of dry matter in grains is mainly imperative for determining the maturity time and overall quality of the crop. DMA was statistically equal among the treatments due to initial slower growth rate (20 DAS) of maize in association with intercrops as well as in pure stand, while sole maize recorded the statistically highest values at all stages, with maximum values recorded at harvest with 2,289.75 g m^{-2} (y-I) and 2,414 g m^{-2} (y II). Legume associations (pea and lentil) were statistically similar to sole maize, while maize + mustard had the lowest dry matter at harvest (1,834.50 g m^{-2} in y I, 1,996.50 g m^{-2} in y-II).

The leaf area index (LAI) (Figure 3) is an essential sign of radiation and precipitation interruption, energy transformation, and water equilibrium which makes it a trustworthy factor for plant growth and development. In general, LAI was increased continuously regardless of treatments and reached maximum at 100 days after sowing, thereafter declined sharply. Sole maize (T_5) recorded statistically highest leaf area

TABLE 4 Influence of leguminous and non-leguminous intercropping systems on plant height (cm) of maize.

Treatments	20 DAS		40 DAS		60 DAS		80 DAS		100 DAS		120 DAS		Harvest	
	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II
M + L	20.43^{a}	21.55^{a}	33.38^{a}	39.64^{a}	92.58^{a}	95.75^{ab}	192.31^{b}	201.94^{a}	261.25^{a}	274.21^{b}	289.53^{a}	301.53^{b}	295.06^{b}	307.63^{a}
M + Mst	20.24^{a}	20.37^{a}	32.08^{a}	39.43^{a}	75.08^{b}	88.28^{b}	181.18^{c}	187.44^{c}	215.21^{c}	220.11^{d}	238.37^{c}	257.85^{d}	249.46^{d}	280.98^{b}
M + W	20.94^{a}	21.13^{a}	32.03^{a}	38.48^{a}	84.34^{ab}	91.60^{b}	183.68^{c}	194.18^{b}	243.75^{b}	251.59^{c}	267.81^{b}	279.85^{d}	275.83^{c}	290.23^{b}
M + P	21.24^{a}	21.59^{a}	34.32^{a}	40.62^{a}	92.65^{a}	99.91^{a}	198.15^{a}	202.60^{a}	266.92^{a}	288.51^{ab}	296.46^{a}	309.91^{ab}	300.37^{ab}	318.38^{a}
M Sole	21.19^{a}	21.78^{a}	34.76^{a}	41.22^{a}	93.97^{a}	100.94^{a}	200.21^{a}	203.54^{a}	271.80^{a}	292.70^{a}	305.41^{a}	314.38^{a}	309.54^{a}	320.04^{a}

M + L = Maize + Lentil, M + Mst = Maize + Mustard, M + W = Maize + Wheat, M + P = Maize + Pea, M Sole = Sole Maize.

TABLE 5 Influence of leguminous and non-leguminous intercropping systems on dry matter accumulation (g m^{-2}) of maize.

Treatments	20 DAS		40 DAS		60 DAS		80 DAS		100 DAS		120 DAS		Harvest	
	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II
M + L	31.07^{a}	34.73^{a}	122.29^{a}	131.87^{a}	434.40^{a}	440.95^{a}	820.90^{a}	853.19^{ab}	1,019.74^{a}	1,064.73^{a}	1,518.25^{bc}	1,675.50^{b}	2,078.25^{b}	2,215.5^{b}
M + Mst	27.07^{a}	32.98^{a}	106.13^{b}	123.98^{b}	387.11^{b}	397.55^{c}	767.27^{b}	788.45^{c}	951.81^{b}	962.40^{b}	1,355^{d}	1,487.75^{c}	1,834.50^{c}	1,996.5^{d}
M + W	27.98^{a}	33.48^{a}	117.52^{a}	129.63^{ab}	390.49^{a}	407.65^{b}	772.94^{b}	820.28^{bc}	968.44^{b}	984.39^{b}	1,397.50^{cd}	1,535.75^{c}	1,894.25^{c}	2,097.5^{c}
M + P	32.95^{a}	36.50^{a}	122.50^{a}	130.32^{ab}	436.25^{a}	441.28^{a}	830.61^{a}	851.50^{ab}	1,028.39^{a}	1,057.26^{a}	1,607.25^{ab}	1,753^{ab}	2,189.75^{ab}	2,365.5^{a}
M Sole	33.12^{a}	38.34^{a}	124.45^{a}	133.55^{a}	442.59^{a}	443.70^{a}	844.56^{a}	863.25^{a}	1,056.35a	1,068.20^{a}	1,700^{a}	1,793.50^{a}	2,289.75^{a}	2,414^{a}

M + L = Maize + Lentil, M + Mst = Maize + Mustard, M + W = Maize + Wheat, M + P = Maize + Pea, M Sole = Sole Maize.

index at all growth stages, reaching maximum values of 4.52 (y-I) and 4.63 (y-II) at 100 DAS. In comparison, maize + pea (T_4) exhibited a slight decline of 6.64% (y-I) and 7.34% (y-II), recording 4.22 and 4.29, respectively. The lowest LAI was observed in maize + mustard (T_2), which showed a 6.64% (y I) and 7.34% (y II) reduction compared to sole maize, with values of 4.22 (y I) and 4.29 (y II) at 100 DAS.

3.2 Effect on yield attributes and yield

The influence of leguminous and non-leguminous intercropping systems on yield attributes of maize (*Zea mays* L.) is presented in Table 6.

Sole maize (T_5) exhibited the maximum cob length (16.60 and 17.58 cm) and cob girth (17.761 and 7.80 cm), closely followed by the maize + pea system (T_4) (16.24 and 17.40 cm and 17.11 and 17.25 cm) respectively during y-I and y-II. In contrast, maize intercropped with mustard (T_2) recorded the lowest values for these traits, with cob length (14.15 and 14.38 cm) and cob girth (13.06 and 13.73 cm), which were significantly lower than the other treatments ($p < 0.05$).

Similarly, sole maize (T_5) and maize + pea (T_4) maintained the highest values for grain rows per cob (17.37 and 17.59 and 16.98 and 17.38, respectively during y-I and y-II), while maize + mustard (T_2) recorded the lowest values (13.85 and 14.73). The seed index, a critical determinant of grain weight followed a similar trend, with the highest values observed in sole maize (33.10 and 32.06 g) and maize + pea (32.60 and 31.68 g) respectively during both the year of experimentation.

The highest grain yield was recorded in the sole maize (T_5) treatment, with values of 9.10 t ha^{-1} (y-I) and 9.21 t ha^{-1} (y-II). This was statistically similar to the maize + pea (T_4) treatment, which recorded 9.03 t ha^{-1} (y-I) and 9.13 t ha^{-1} (y-II). Compared to the lowest yield recorded in maize + mustard (T_2) (7.99 t ha^{-1} in y-I and 8.09 t ha^{-1} in y-II), the yield in T_5 increased by 13.91% (y-I) and 13.85% (y-II), while in T_4, the yield increased by 13.02% (y-I) and 12.86% (y-II).

3.3 Effect on weed density (no. m^{-2})

The influence of leguminous and non-leguminous intercrops on weed density (Figure 4) in maize was evaluated at different growth stages, revealing the superior weed suppression potential of legume-based systems compared to sole maize and non-legume intercrops.

At 20 DAS leguminous systems (maize + lentil, maize + pea) exhibited the lowest weed densities, with maize + lentil recording 39.43 and 41.43 m^{-2} (y-I and y-II). Sole maize had the highest weed density (45.16 and 59.72 m^{-2}), reflecting limited weed suppression due to slow canopy development. While at 40 DAS maize + pea and maize + lentil continued to show reduced weed densities (39.11 and 41.71 and 40.18 and 42.63 m^{-2} respectively). Sole maize recorded significantly higher weed density (58.06 and 65.72 m^{-2}), emphasizing its inferior weed suppression ability.

3.4 Effect on weed biomass (g m^{-2})

The study evaluated weed biomass under various intercropping systems in maize at different growth stages. Legume-based

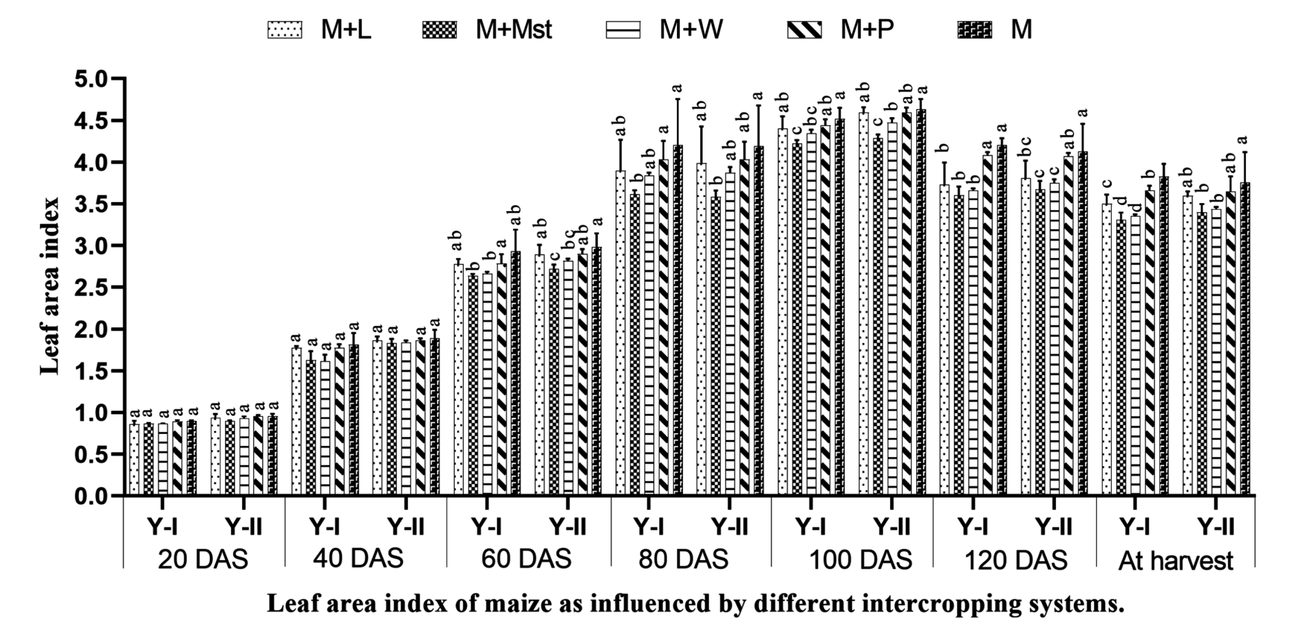

FIGURE 3
Leaf area index (LAI) of maize as influenced by different intercropping systems.

TABLE 6 Influence of leguminous and non-leguminous intercropping systems on yield attributes and yield (t ha^{-1}) of maize.

Treatments	Cob length (cm)		Cob girth (cm)		Grain rows cob^{-1}		Grains row^{-1}		Seed index		Grain yield (t ha^{-1})	
	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II
M + L	15.99^{a}	16.67^{a}	16.78^{b}	17.10^{a}	16.90^{a}	17.33^{a}	31.70^{ab}	32.53^{ab}	31.40^{b}	31.89^{ab}	8.80^{a}	8.90^{ab}
M + Mst	14.15^{b}	14.38^{b}	13.06^{d}	13.73^{c}	13.85^{b}	14.73^{b}	20.30^{c}	21.22^{c}	28.38^{d}	28.73^{c}	7.99^{b}	8.09^{c}
M + W	14.20^{b}	14.43^{b}	14.01^{c}	14.65^{b}	14.50^{b}	15.02^{b}	28.45^{b}	28.84^{b}	29.85^{c}	30.06^{bc}	8.17^{b}	8.62^{b}
M + P	16.24^{a}	17.40^{a}	17.11^{ab}	17.25^{a}	16.98^{a}	17.38^{a}	33.60^{ab}	33.98^{ab}	32.60^{a}	31.68^{ab}	9.03^{a}	9.13^{a}
M Sole	16.60^{a}	17.58^{a}	17.76^{a}	17.80^{a}	17.37^{a}	17.59^{a}	36.65^{a}	34.90^{a}	33.10^{a}	32.06^{a}	9.10^{a}	9.21^{a}

M + L = Maize + Lentil, M + Mst = Maize + Mustard, M + W = Maize + Wheat, M + P = Maize + Pea, M Sole = Sole Maize.

intercropping consistently showed superior weed suppression compared to non-leguminous systems and sole maize. During early crop growth stages (20 DAS) leguminous intercrops recorded significantly lower weed biomass, with maize + lentil having the least (34.70 and 46.06 g m^{-2} in y-I and y-II, respectively). Sole maize had the highest weed biomass (50.58 and 65.61 g m^{-2}), indicating limited weed suppression due to poor canopy closure. At 40 DAS weed biomass was lowest in maize + pea (50.85 and 56.64 g m^{-2}) and maize + lentil, while sole maize exhibited significantly higher biomass (98.71 and 102.53 g m^{-2}). Non-leguminous maize + mustard showed moderate suppression (59.11 and 61.74 g m^{-2}).

3.5 Effect on weed smothering efficiency

Weed smothering, the ability of crops to suppress weed growth through competition for light, nutrients, and space, is a critical component of weed management strategies. This study evaluates that, legume-based intercropping systems consistently demonstrated superior weed suppression across all growth stages of maize compared to non-leguminous systems (Figure 5).

At 20 DAS maize + lentil (30.50%) and maize + pea (29.16%) showed the highest weed smothering effects. Non-legumes like maize + mustard (27.71%) and maize + wheat (27.91%) had lower effects. Maize + pea (46.56%) and maize + lentil (44.44%) exhibited the best suppression at 40 DAS, while maize + wheat (41.36%) and maize + mustard (39.91%) lagged. At 60 DAS, Maize + pea (48.94%) and maize + lentil (46.45%) continued to surpass non-legumes like maize + wheat (43.01%) and maize + mustard (41.02%). During 80 DAS, Maize + lentil (46.97%) and maize + pea (46.75%) maintained the highest suppression, with lower effects from maize + wheat (43.95%) and maize + mustard (38.55%). During harvest, Maize + lentil (36.12%) and maize + pea (34.38%) sustained long-term weed suppression, while maize + mustard (29.54%) was the least effective.

3.6 Intercropping indices

The intercropping of maize with leguminous and non-leguminous crops demonstrated varying impacts on maize equivalent yield (MEY), land equivalent ratio (LER), relative yield total (RYT), area

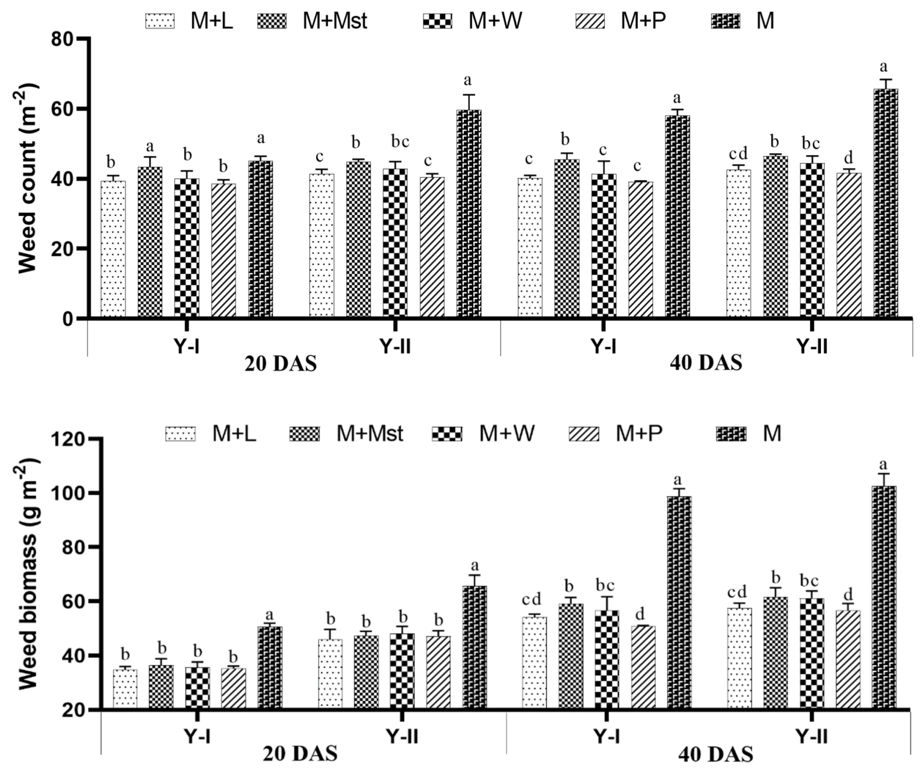

FIGURE 4
Weed density (m^{-2}) and weed biomass (g m^{-2}) of maize as influenced by different intercropping systems.

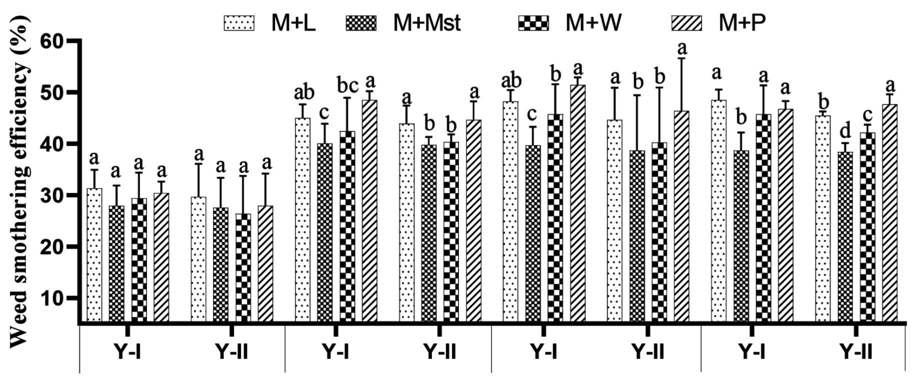

FIGURE 5
Weed smothering efficiency of different intercrops in association with maize at 20, 40, 60, and 80 days after sowing.

time equivalent ratio (ATER) and monetary advantage index (MAI) across y-I and y-II (Table 7).

The maize + pea (T_4) intercropping system recorded the highest MEY with yields of 14.77, 15.54 t ha^{-1} during y-I and y-II, respectively. This was followed by the maize + lentil (T_1) system which achieved MEYs of 10.62 and 10.87 t ha^{-1} during y-I and y-II, respectively. Moderate MEY were observed in the maize + wheat (T_3) and maize + mustard (T_2) systems with pooled yields of 10.50 and 10.24 t ha^{-1}, respectively. The lowest MEY was recorded in sole maize with a pooled yield of 9.15 t ha^{-1}.

The maize + mustard (T_2) system demonstrated the highest LER values of 1.57 and 1.59 during y-I and y-II, respectively, followed by maize + pea (T_4) system with LER values of 1.49 and 1.51. The maize + wheat (T_3) had the lowest LER with values of 1.21 and 1.25 respectively, indicating land inefficient (Figure 6).

In terms of RYT the maize-lentil (T_1) system achieved the highest with values of 0.91 in both years showing effective complementary growth between maize and lentil. The maize + pea (T_4) system showed a moderate RYT of 0.75 in both years, with its economic advantage driven by the early sale of green pods. Conversely the maize-wheat (T_3) system had the lowest pooled RYT (0.66 and 0.68, respectively, during both the year), due to prolonged competition and reduced plant density.

The maize + mustard (T_2) system had a high Area Time Equivalent Ratio (ATER) of 1.18 and 1.21 followed by maize + pea (T_4) with

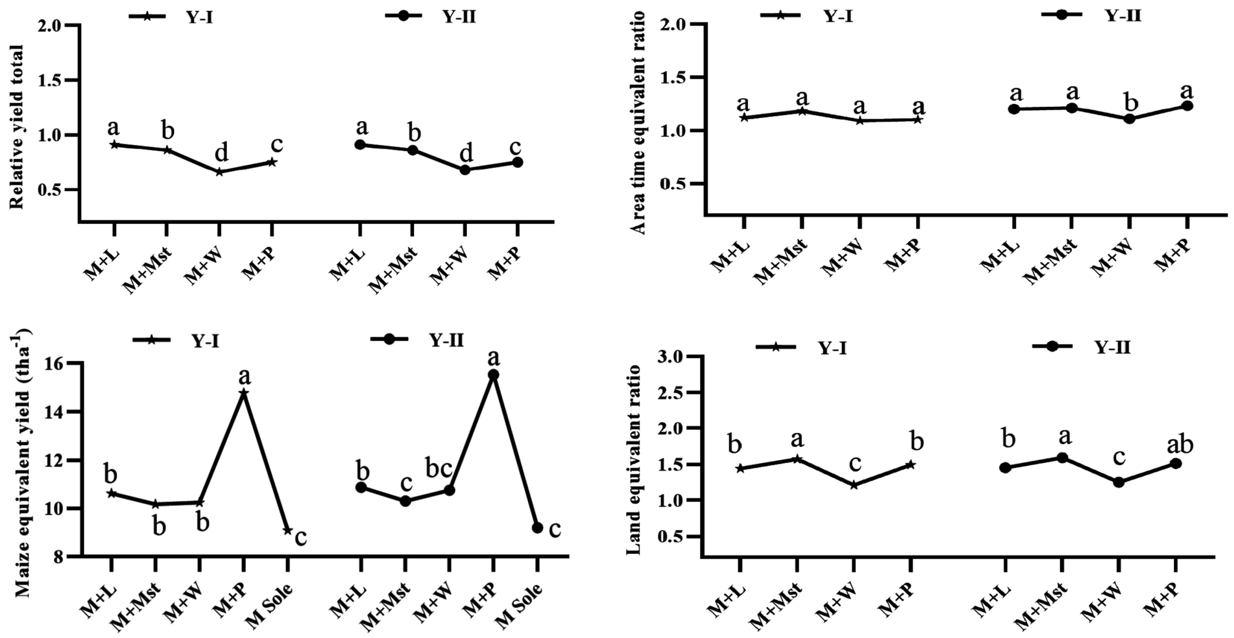

FIGURE 6
The impact of leguminous and non-leguminous intercropping systems on intercropping indices of maize.

ATER values of 1.10 and 1.23 whereas, maize + wheat (T_3) had lowest ATER of 1.09 and 1.11 in y-I and y-II, respectively.

3.7 Effect on nutrient uptake (kg ha^{-1})

The impact of leguminous and non-leguminous intercropping systems on nutrient uptake is presented in Table 8.

In terms of nitrogen uptake, the sole maize system recorded values of 170.49 kg ha^{-1} and 166.37 in y-I and y-II, respectively. The intercropping systems involving leguminous crops particularly maize + pea (T_4) and maize + lentil (T_1) also performed well in terms of nitrogen uptake with pooled values of 156.02 kg ha^{-1} and 153.03 kg ha^{-1}, respectively. For phosphorus uptake the sole maize treatment again outperformed the intercropping systems with phosphorus uptake of 34.73 and 33.96 kg ha^{-1} in y-I and y-II, respectively. However, maize + pea (T_4) recorded relatively high phosphorus uptake of 32.91 and 31.15 kg ha^{-1}, respectively. The phosphorus uptake in non-leguminous systems like maize + mustard (T_2) and maize + wheat (T_3) was lower with the lowest uptake seen in the mustard system (26.28 and 25.73 kg ha^{-1} in y-I and y-II respectively). Potassium uptake followed a similar trend with sole maize showing the highest uptake (119.35 and 117.17 kg ha^{-1}) followed by legume-based systems such as maize + pea (114.13 and 113.86 kg ha^{-1}). The non-leguminous treatments particularly maize + mustard (T_2) exhibited the lowest potassium uptake (93.51 and 92.90 kg ha^{-1}).

3.8 Effect on soil chemical properties

The impact of leguminous and non-leguminous intercropping systems on soil chemical properties presented in Table 7.

Leguminous intercrops particularly maize + pea (0.71 and 0.72%) and maize + lentil (0.69 and 0.71%) demonstrated higher organic carbon content compared to non-leguminous intercrops and sole maize, respectively, during y-I and y-II.

The maize + pea (T_4) intercropping system showed the highest available nitrogen (145.25 and 148.75 kg ha^{-1}) followed closely by maize + lentil (T_1) with 141.00 and 143.25 kg ha^{-1} in both the year of experimentation. Non-leguminous intercrops (maize + mustard and maize + wheat) and sole maize exhibited lower soil nitrogen levels. Interestingly, the maize + mustard (T_2) system showed the highest available phosphorus (27.50 and 29.20 kg ha^{-1}, respectively, during y-I and y-II) followed by maize + wheat (T_3) with 27.25 and 28.75 kg ha^{-1}, respectively. Leguminous intercrops showed slightly lower phosphorus levels. The maize + mustard (T_2) system showed the highest available potassium content (127.0 and 130.25 kg ha^{-1}, respectively, during y-I and y-II), even though all are statistically similar (Table 8).

3.9 Economics of production system

The impact of leguminous and non-leguminous intercropping systems on economics of maize is presented in Table 9.

The highest cost of cultivation (₹83,211 and ₹85,771 ha^{-1}), gross returns (₹289,714 and ₹324,844 ha^{-1}), net return (₹206,503 and ₹239,073 ha^{-1}) and benefit–cost ratio (2.48 and 2.79) in the y-I and y-II respectively, was observed in the maize + pea (T_4) treatment. In contrast, sole maize (T_5) recorded the lowest cost of cultivation (₹64,431 and ₹66,086), lowest gross return (₹178,493 and ₹192,384 ha^{-1}), lowest net return (₹114,062 and ₹126,298 ha^{-1}), lowest BCR (1.77 and 1.91), in the y-I and y-II. The maize + lentil (T_1), maize + mustard (T_2) and maize + wheat (T_3) systems had intermediate costs of cultivation with pooled values ranging from ₹69,470 to ₹70,744 ha^{-1},

TABLE 7 Influence of leguminous and non-leguminous intercropping systems on soil and plant nutrient status of maize.

Treatments	Soil nutrient status								Nutrient uptake					
	Organic Carbon (%)		Avail. Nitrogen (kg ha^{-1})		Avail. Phosphorus (kg ha^{-1})		Avail. Potassium (kg ha^{-1})		Nitrogen uptake (kg ha^{-1})		Phosphorus uptake (kg ha^{-1})		Potassium uptake (kg ha^{-1})	
	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II
M + L	0.69^{ab}	0.71^{a}	141^{b}	143.25^{b}	25.75^{bc}	27.15^{c}	126^{a}	129.50^{a}	154^{b}	152.06^{b}	30.94^{b}	30.09^{b}	107.16^{b}	106.60^{b}
M + Mst	0.66^{b}	0.68^{a}	125.50^{c}	131^{c}	27.50^{a}	29.20^{a}	127^{a}	130.25^{a}	138.12^{c}	137.36^{c}	26.28^{c}	25.73^{c}	93.51^{c}	92.90^{c}
M + W	0.65^{b}	0.69^{a}	124.50^{cd}	129.50^{cd}	27.25^{a}	28.75^{ab}	126.50^{a}	130^{a}	141.46^{c}	139.25^{c}	27.84^{c}	26.86^{c}	96.48^{c}	95.33^{c}
M + P	0.71^{a}	0.72^{a}	145.25^{a}	148.75^{a}	25.50^{c}	26.90^{c}	125.75^{a}	129^{a}	158^{b}	154.04^{b}	32.91^{ab}	31.15^{ab}	114.13^{ab}	113.86^{a}
M Sole	0.66^{b}	0.67^{a}	122.25^{d}	126.25^{d}	26.75^{ac}	28.25^{b}	123^{b}	128.50^{a}	170.49^{a}	166.37^{a}	34.73^{a}	33.96^{a}	119.35^{a}	117.17^{a}

M + L = Maize + Lentil, M + Mst = Maize + Mustard, M + W = Maize + Wheat, M + P = Maize + Pea, M Sole = Sole Maize.

gross returns ranging from of ₹207,431 to ₹217,821 ha^{-1} and net return (₹120,180–₹147,307 ha^{-1}) and BCR ranging from 1.84 to 2.63.

3.10 Interaction study

Plant Height (PH) shows a significant positive correlation with dry matter (DM) ($r = 0.97$), leaf area index (LAI) ($r = 0.95$), and cob length (CL) ($r = 0.95$). These correlations confirm the importance of plant stature in determining overall crop growth and development. Dry Matter Accumulation (DM) is positively correlated with GY ($r = 0.97$), LAI ($r = 0.99$), and CL ($r = 0.96$). High DM indicates better vegetative growth, which is essential for reproductive success. Leaf Area Index (LAI) correlates strongly with GY ($r = 0.95$) and PH ($r = 0.95$). A higher LAI contributes to better light interception and photosynthesis. Grain Yield (GY) shows strong positive correlations with cob girth (CG) ($r = 0.98$), cob length (CL) ($r = 0.95$), and grains per row (GPR) ($r = 0.98$). These results underscore the importance of cob characteristics in determining final yields. Seed Index (SI) correlates positively with GY ($r = 0.99$). This indicates that larger seeds contribute significantly to higher yields. Weed Density (WD) negatively correlates with GY ($r = -0.78$). Treatments with higher WD result in lower yields and reduced resource use efficiency. Weed Biomass (WB) negatively correlates with GY ($r = -0.79$). Higher WB indicates reduced crop growth due to competition. Maize Equivalent Yield (MEY) correlates weakly with GY ($r = 0.28$) but shows negative correlations with WD ($r = -0.78$). This suggests that MEY is more influenced by weed control and resource efficiency (Figure 7).

TABLE 8 Yield of intercrops and their maize equivalent yield (MEY).

Intercrops	Intercrop yield (t ha^{-1})		Maize equivalent yield (MEY) (t ha^{-1})	
	Y-I	Y-II	Y-I	Y-II
Lentil	0.60	0.64	1.82	1.97
Mustard	0.78	0.82	2.18	2.21
Wheat	1.92	1.96	2.08	2.13
Pea	4.51	4.63	5.74	6.42

4 Discussion

4.1 Effect growth attributes

The consistent superiority of sole maize in both plant height, dry matter accumulation across all growth stages can be attributed to its unrestricted access to essential resources such as nutrients, light, and moisture, with no competition from companion crops, aligning with findings by Li et al. (2014). Among intercrops, maize + pea and maize + lentil performed well, particularly at later stages, as legumes enhance soil nitrogen availability through biological fixation, with peas being more efficient than lentils (Ghosh, 2006). Non-leguminous intercrops, such as maize + mustard and maize + wheat, showed the lowest growth due to higher competition for resources. These results underscore the productivity and sustainability of legume-based intercropping systems, as supported by Xu et al. (2020) and Jensen et al. (2020).

Sole maize consistently exhibited the highest LAI across all growth stages due to the absence of interspecific competition, allowing unimpeded canopy expansion and optimal resource utilization (Li et al., 2020). Legume-based intercrops, such as maize + pea and maize + lentil, showed higher LAI compared to non-leguminous intercrops, particularly in later growth stages, due to nitrogen fixation and complementary resource use (Latati et al., 2017). In contrast, non-leguminous intercrops like maize + mustard recorded the lowest LAI, attributed to increased competition for nutrients and moisture (Li et al., 2024). These findings emphasize the advantages of sole maize and legume-based intercropping for canopy development and highlight challenges in non-leguminous systems (Yang et al., 2024).

4.2 Effect on yield attributes and yield

Intercropping influences maize growth and yield by affecting nutrient uptake patterns. Legume-based intercropping, particularly maize + pea, exhibited superior performance in yield attributes due to the nitrogen-fixing ability of legumes, which enhances nitrogen availability in the soil (Li et al., 2020; Begam et al., 2024). Pea establishes symbiosis with Rhizobium bacteria, contributing biologically fixed nitrogen to the system, thereby benefiting maize in terms of nutrient supply (Lithourgidis et al., 2011). This process reduces nitrogen dependency on external fertilizers and promotes higher grain yield compared to non-legume intercrops. Conversely, mustard and wheat are non-leguminous crops that lack biological nitrogen fixation. Their

TABLE 9 Influence of leguminous and non-leguminous intercropping systems on economics of maize.

Treatments	Economics of Maize crop							
	Cost of cultivation (₹ ha^{-1})		Gross return (₹ ha^{-1})		Net return (₹ ha^{-1})		Benefit–cost ratio	
	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II	Y-I	Y-II
M + L	69,426[c]	71,646[c]	208,401[b]	227,242[b]	138,975[b]	155,640[b]	2.0[b]	2.17[b]
M + Mst	68,527[d]	70,413[d]	199,617[b]	215,245[c]	131,090[b]	144,832[b]	1.91[b]	2.06[bc]
M + W	69,842[b]	71,646[b]	201,136[b]	224,673[bc]	131,294[b]	153,027[b]	1.88[bc]	2.14[b]
M + P	83,211[a]	85,771[a]	289,714[a]	324,844[a]	206,503[a]	239,073[a]	2.48[a]	2.79[a]
M Sole	64,431[e]	66,086[e]	178,493[c]	192,384[d]	114,062[c]	126,298[c]	1.77[c]	1.91[c]

M + L = Maize + Lentil, M + Mst = Maize + Mustard, M + W = Maize + Wheat, M + P = Maize + Pea, M Sole = Sole Maize.

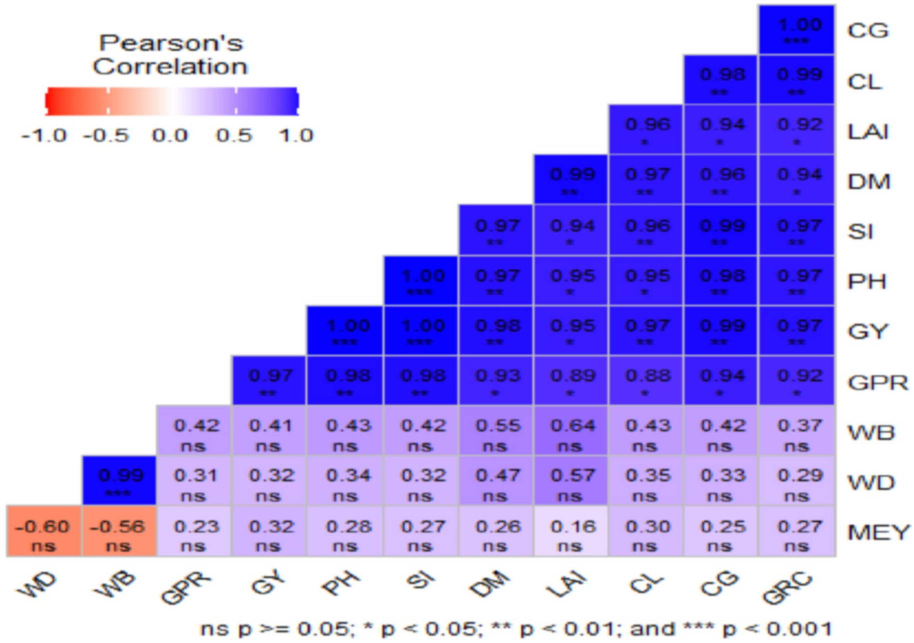

FIGURE 7
Correlation studies between growth, yield and weed parameters of maize as impacted by leguminous and non-leguminous intercropping systems. PH-Plant height (cm), DM-Dry matter accumulation (g m^{-2}), LAI-Leaf area index, CL-Cob length (cm), CG-Cob girth (cm), GRC-Grain rows cob^{-1}, GPR-Grains row^{-1}, SI-Seed index, GY-Grain yield (t ha^{-1}), MEY-Maize equivalent yield (t ha^{-1}), WD-Weed density (g), WB-Weed biomass (g m^{-2}).

high nutrient demand, particularly for nitrogen and phosphorus, leads to direct competition with maize, often resulting in lower yield attributes (Maitra et al., 2024a,b). Mustard, being a fast-growing and highly competitive crop, aggressively extracts nutrients from the soil, which suppresses maize growth, especially in the early vegetative stages (Dhima et al., 2007). Additionally, wheat has a dense root system that can compete with maize for both nutrients and water, reducing maize's ability to uptake essential macronutrients like nitrogen, phosphorus, and potassium (Zhang et al., 2019).

The rooting architecture of component crops in an intercropping system plays a crucial role in nutrient acquisition and water uptake. Maize has a fibrous root system that can explore a large volume of soil but primarily remains within the upper 60 cm of the soil profile (Zhao et al., 2017). Pea, being a shallow-rooted legume, primarily utilizes nutrients from the top 30–40 cm of the soil, thereby reducing competition for deeper soil nutrients and allowing maize to access resources more efficiently (Ghosh, 2006). This complementary root distribution minimizes interspecific competition, leading to improved maize growth and yield. On the other hand, mustard and wheat exhibit root systems that overlap significantly with maize. Mustard has a deep taproot system that extends beyond one meter, allowing it to extract water and nutrients aggressively from both shallow and deep soil layers, often outcompeting maize in dry conditions (Dhima et al., 2007). Similarly, wheat, with its dense and fibrous root system, competes intensively with maize for soil nutrients in the same rooting zone (Maitra et al., 2024a,b). This leads to reduced nutrient uptake by maize, contributing to its lower cob length, cob girth, and seed index in these intercropping treatments.

The differential plant height and canopy architecture of intercropping components influence light interception, which affects maize productivity. Maize, being a tall-growing C_4 crop, has a high light requirement for efficient photosynthesis and dry matter accumulation (Tilman et al., 2011). In maize + pea intercropping, the shorter canopy height of pea allows maize to receive maximum sunlight without shading effects, promoting better biomass accumulation and grain filling (Lithourgidis et al., 2011). In contrast, wheat and mustard are both taller than pea and have dense foliage, which can interfere with maize's light capture. Wheat has an erectophile leaf arrangement that competes with maize in the mid-canopy region, potentially reducing photosynthesis efficiency (Ghosh, 2006). Mustard grows rapidly and has broad leaves that shade maize plants, especially during early growth stages, further limiting maize photosynthetic capacity (Maitra et al., 2024a,b). This shading effect likely contributes to the observed reduction in grain rows per cob, grains per row, and ultimately grain yield in maize + mustard systems.

4.3 Effect on weed density (no. m^{-2})

Across all stages the leguminous intercrops (pea and lentil) consistently reduced weed density more effectively than non-leguminous intercrops (mustard and wheat) (Sannagoudar et al., 2024). Leguminous intercrops, such as pea and lentil, consistently reduce weed density more effectively than non-leguminous crops like mustard and wheat due to several ecological and agronomic advantages. Their dense and widespread canopy architecture shades the soil surface, inhibiting weed germination and growth, as highlighted by Lithourgidis et al. (2011). In addition to physical suppression, legumes produce allelopathic compounds, such as phenolic acids in peas, that further suppress weed seed germination and growth (Iqbal et al., 2020). Legumes also utilize soil moisture more efficiently, indirectly limiting the water available for weed seedlings, reducing their growth potential (Liu et al., 2022; Naher et al., 2021). Furthermore, leguminous crops improve soil health by enhancing its structure and microbial activity, creating conditions less favorable for weeds while promoting nutrient cycling (Bedoussac et al., 2015). Lastly, the root systems of legumes effectively explore the soil without directly competing with maize, optimizing resource availability for the intercrop and depleting resources for weeds. In contrast, non-leguminous crops like mustard or wheat often compete more directly with maize, thereby leaving weeds less suppressed (Singh and Yadav, 2019). These synergistic benefits make legume-based systems superior in managing weed populations effectively. Non-leguminous intercrops while still providing some weed suppression were less effective in comparison, likely due to their lower ground coverage with canopy production and less efficient resource use (Ghosh, 2006).

4.4 Effect on weed biomass (g m^{-2})

Across all growth stages, leguminous intercrops consistently demonstrated a stronger weed suppression ability compared to non-leguminous intercrops resulting least biomass production. The ability of leguminous crops such as lentil and pea to fix atmospheric nitrogen and create a denser canopy early in the season provides them with an advantage in outcompeting weeds for resources. Non-leguminous crops like mustard and wheat while still providing some weed suppression were less effective in reducing weed biomass particularly at later stages. Similar findings were reported by Duchene et al. (2017) who noted that leguminous crops enhanced weed suppression and gained less weed biomass due to more competition for resources. The long-term benefits of leguminous crops particularly in reducing weed biomass by creating a more competitive growing environment for maize are evident at this final stage (Wang and Li, 2024).

4.5 Effect on weed smothering

Across all growth stages leguminous intercrops particularly maize + pea and maize + lentil consistently exhibited a higher weed smothering effect than non-leguminous intercrops. The superior weed smothering ability of leguminous crops at early stage can be attributed to their relatively faster initial growth and canopy development which limits the light available to weeds. Moreover, the ability of leguminous crops to fix atmospheric nitrogen enhances soil health and promotes faster crop growth contributed to their superior weed suppression and vigorous canopy. Non-leguminous intercrops, though beneficial were less effective at smothering weeds, especially at the later stages of crop growth (Corre-Hellou et al., 2011). The results highlight the enduring weed-suppressing advantages of leguminous crops, which sustain a competitive canopy and nutrient supply that effectively inhibit weed growth over time (Sahu and Singh, 2019; Meena et al., 2024).

4.6 Intercropping indices

Non-leguminous intercropping systems such as maize-wheat and maize-mustard recorded lower maize equivalent yields (MEY). In the maize-mustard system, the vigorous initial growth of mustard suppressed maize development, reducing its yield potential (Fukai and Trenbath, 2020). In maize-wheat systems, prolonged growth durations lead to intense competition for water, nutrients, and light, negatively impacting maize yields despite high individual crop potential (Sharma et al., 2023).

The higher Land Equivalent Ratio (LER) in maize-mustard systems is linked to effective spatial resource utilization by low-yielding mustard varieties (B-9), minimizing population reduction and enhancing land use efficiency (Malézieux et al., 2022). Conversely, the lower LER in maize-wheat systems results from reduced plant densities and prolonged competition, which limit efficient resource use (Lithourgidis et al., 2011).

Legume-based intercropping systems demonstrate higher relative yield total (RYT) due to nitrogen fixation by legumes like lentils, which complement maize growth during long-duration associations. In contrast, lower RYT in maize-pea systems is observed due to early harvest of peas as green pods, which reduces total biomass production despite economic benefits (Ghosh, 2006; Ali et al., 2022).

The Area Time Equivalent Ratio (ATER) provided insights into the temporal efficiency of different intercropping systems. The maize-mustard and maize-pea systems showed favorable ATER due to the short growth duration of these crops and efficient use of land and time resources (Bi et al., 2016). Maize-lentil systems also perform well in ATER, driven by effective resource complementarities across spatial and temporal scales (Lithourgidis et al., 2023).

4.7 Effect on nutrient uptake (kg ha^{-1})

Enhanced nitrogen uptake in legume-based systems can be attributed to the biological nitrogen fixation capabilities of leguminous crops which enhance soil nitrogen content benefiting the intercropped maize (Ghosh, 2006). Significant phosphorus uptake by maize + pea, likely due to the early and fast growth of the pea crop which allows it to effectively capture phosphorus before maize enters its peak nutrient demand phase (An et al., 2024). Lower phosphorus uptake in maize + mustard may be due to greater competition for nutrients between the non-leguminous crops as both species require similar resources (Li et al., 2014; Bi et al., 2019). Lower uptake of potassium by maize + mustard, compared to legume-based intercropping could be explained by the absence of nitrogen fixation benefits and the competitive nature of mustard which likely reduces resource availability for maize (Dhima et al., 2007).

Unlike legumes, mustard does not contribute to biological nitrogen fixation. In legume-based intercropping systems, the nitrogen fixed by legumes benefits companion crops like maize, which can indirectly enhance nutrient availability (Tang et al., 2014; Bedoussac et al., 2015). The absence of this benefit in maize + mustard systems could lead to reduced potassium uptake due to limited nitrogen availability, which is critical for optimal plant growth.

In sole maize, there is no competition from other crops for nutrients, water, and light. This allows maize to fully utilize the available soil nutrients, leading to greater uptake of N, P, and K. In contrast, intercropping systems introduce competition, particularly when the companion crop has similar nutrient demands (Ghosh, 2006; Hauggaard-Nielsen et al., 2001). Apart from that maize has an extensive fibrous root system that efficiently explores the soil for nutrient uptake. In sole cropping, maize roots have unrestricted access to soil nutrients, whereas in intercropping, root interactions with companion crops can either enhance or restrict nutrient acquisition depending on species compatibility (Zhao et al., 2017).

In intercropping, nutrient partitioning between species can reduce the individual crop's nutrient uptake. In sole maize systems, all available soil nutrients are accessible to maize alone, enhancing its uptake of N, P, and K. In contrast, legume-based systems may contribute nitrogen but do not necessarily increase P and K availability to maize due to competition (Lithourgidis et al., 2011). Certain intercrops, such as mustard, exhibit strong competitive effects and can suppress maize nutrient uptake due to their rapid nutrient extraction and allelopathic effects (Dhima et al., 2007). Sole maize avoids these negative interactions, leading to better overall nutrient acquisition. In sole cropping, applied fertilizers are fully available for maize uptake without any interspecies competition. Studies have shown that in mixed cropping systems, nutrient uptake efficiency can be lower due to differential root architecture and nutrient requirements of the associated crops (Zhang et al., 2019).

Overall the findings highlight the importance of leguminous intercropping in enhancing nutrient uptake particularly nitrogen due to their symbiotic nitrogen-fixing abilities whereas non-leguminous crops such as mustard and wheat tend to increase competition for nutrients resulting in lower nutrient uptake and overall growth performance.

4.8 Effect on soil chemical properties

Increase in OC can be attributed to enhanced microbial activity associated with legume-based intercropping systems (Bedoussac et al., 2015). Overall, the results suggest that leguminous intercrops have a more positive impact on soil chemical properties compared to non-leguminous intercrops and sole maize cultivation (Sharma et al., 2024). The increased organic carbon content in legume-based systems indicate their potential for enhancing soil fertility and sustainability in intercropping practices (Latati et al., 2017; Phiri and Willard, 2023).

Significant increase in available nitrogen in legume-based systems can be attributed to the biological nitrogen fixation capability of legumes which enhances soil nitrogen content (Bedoussac et al., 2015). Enhanced phosphorus mobilization and uptake efficiency in certain non-leguminous intercrops possibly through root exudates or mycorrhizal associations (Xue et al., 2016). Overall, these results indicate that leguminous intercrops particularly maize + pea and maize + lentil significantly improve soil nitrogen availability (Gong et al., 2024). Non-leguminous intercrops especially maize + mustard seem to enhance phosphorus availability (Liu and Watson, 2021). The impact on potassium availability appears to be less pronounced across different intercropping systems (Jensen et al., 2020). Maize exhibits the highest potassium content in intercropping systems due to its strong demand for potassium, facilitated by its extensive root system, high transpiration rate, and rapid growth. These traits enable efficient potassium absorption, even under competitive conditions, unlike legumes and non-leguminous crops, which focus more on nitrogen and phosphorus dynamics.

The observed differences in nutrient availability underscore the importance of choosing appropriate intercropping combinations based on specific soil nutrient management goals (Ma et al., 2024). Long-term studies may provide further insights into the sustained impacts of these intercropping systems on soil chemical properties and overall soil health (Liang et al., 2024; Tiwari et al., 2024).

4.9 Economics of production system

The superior economic performance of the maize + pea can be attributed to the symbiotic relationship between maize and legumes, specifically pea, which improves soil nitrogen availability leading to enhanced crop yields and returns. Study done by Caihong et al. (2018), have documented similar findings highlighting the positive impact of legume intercropping on the nutrient-use efficiency and profitability of cereal crops. Additionally, legumes contribute to long-term soil health, reducing the need for external fertilizers and lowering cultivation costs over time. On the other hand, sole maize cultivation, despite having the lowest cost of production consistently resulted in lower gross and net returns as well as the lowest BCR (Caihong et al., 2018). This is likely due to the absence of the complementary benefits observed in legume-based intercropping systems (Xiaoyan et al., 2021). Research indicates that mono cropping can lead to nutrient depletion and reduced soil fertility over time which may explain the lower profitability of the sole maize treatment (Lithourgidis et al., 2011).

The findings from this economic analysis underscore the value of intercropping particularly with legumes for enhancing maize productivity and profitability. The use of pea in particular offers a promising strategy for farmers seeking to optimize both yield and economic returns while maintaining sustainable soil management practices.

4.10 Interaction

Enhanced plant height leads to increased light interception by the canopy, optimizing photosynthetic activity. Taller plants in intercropping systems often benefit from better spatial positioning, which improves their access to sunlight and subsequently boosts their biomass production (Zhang et al., 2017). Legumes contribute organic matter to the soil through leaf litter and root exudates, enriching its organic carbon content. The increased DM in intercropping systems correlates with improved soil structure, water retention, and microbial activity (Meena et al., 2024). These factors collectively support higher productivity in legume-based systems. Intercropping promotes diverse canopy architecture, enhancing the leaf area index. This maximizes the interception of sunlight and efficient use of resources like water and nutrients (Xiao et al., 2021). Improved LAI is particularly evident in legume-maize systems due to complementary nutrient uptake patterns. Legumes, by fixing atmospheric nitrogen, provide nutrient benefits to companion crops, but their contribution also extends to enhancing phosphorus availability and increasing soil microbial biodiversity. These factors play a crucial role in boosting yields (Akshit et al., 2023). The dense canopy formed by legumes reduces sunlight availability for weeds, effectively suppressing their growth. Additionally, the allelopathic compounds produced by certain legumes further inhibit weed biomass (Maitra et al., 2024a,b). This weed suppression contributes significantly to the efficient utilization of resources. Better resource partitioning in intercropping systems, supported by diverse root architectures and complementary nutrient demands, leads to improved maize equivalent yield. The ability of legumes to enhance soil fertility, reduce pests, and manage weeds also plays a pivotal role (Ali et al., 2020).

5 Conclusion

This extensive study on legume and non-legume intercropping with rabi maize in the eastern sub-Himalayan region of India offers valuable insights into sustainable agricultural practices. The results demonstrate that intercropping, particularly the maize and pea combination, significantly enhances yield attributes, nutrient uptake and productivity. Additionally, this combination effectively suppresses weed growth and contributes to economic sustainability. The research emphasizes the relevance of intercrop evaluation metrics such as land equivalent ratio (LER), area time equivalent ratio (ATER) and relative yield total (RYT), which are critical in identifying the most efficient intercrop systems for rabi maize. These indices help optimize resource use and ensure better productivity outcomes. Importantly, the study's implications extend beyond the specific regional focus. The successful intercropping strategies identified here, particularly maize + pea, can be adapted to similar agro-ecological zones worldwide, aiding the global pursuit of sustainable agriculture and food security. For future directions, the study suggests exploring the long-term effects of these intercropping systems on soil health and biodiversity. Particular attention should be paid to below-ground interactions, such as rhizosphere microbial activity and root system morphology. Moreover, assessing the scalability and adaptability of these systems in varied agricultural environments, under different environmental and socio-economic conditions, is essential. In conclusion, the study highlights the significant role of traditional agricultural practices in making farming systems more sustainable, productive, and environmentally responsible. The knowledge generated not only addresses local challenges in the eastern sub-Himalayan region but also contributes to the global objective of achieving sustainable food production through efficient resource management.

5.1 Limitations

The experiment was conducted over two rabi seasons only. This limited temporal scope might not capture year to year climatic variability and its effects on crop interactions, nutrient cycling and long-term soil health. The study evaluated only four intercrops with maize. Broader exploration of other legume and non-legume species, including oilseeds and cover crops, could provide additional insights into optimal combinations for different agro-ecological zones. The research was confined to the sub-Himalayan plains of West Bengal. Agro-climatic variability across regions means that the findings may not be directly transferable to other zones without localized validation and adaptation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Author contributions

HM: Investigation, Methodology, Writing – original draft, Writing – review & editing, Data curation. PP: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. PA: Data curation, Writing – review & editing, Conceptualization. AA: Investigation, Methodology, Software, Writing – review & editing. SK: Formal analysis, Project administration, Writing – review & editing, Methodology. SD: Data curation, Formal analysis, Writing – review & editing, Software. FR: Methodology, Visualization, Writing – review & editing. AT: Methodology, Validation, Writing – review & editing. BD: Resources, Visualization, Writing – review & editing. PS: Methodology, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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