



Mycorrhiza Assisted Intercropping of Pinto Bean (*Phaseolus vulgaris* L.) with Dill (*Anethum graveolens* L.): Yield, Essential Oil Quality and Intercropping Efficiency in a Temperate Semi-arid System

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ABSTRACT

Background: Intercropping legumes with compatible aromatic crops can enhance land use efficiency and economic returns, particularly in semi arid environments. Arbuscular mycorrhizal fungi (AMF) may further improve nutrient acquisition, crop productivity and quality traits in such systems.

Methods: A field experiment was conducted during the 2023 growing season at the Agricultural Research Farm of the University of Tabriz, Iran, using a factorial randomized complete block design with three replications. Six pinto bean-dill planting patterns were evaluated with and without AMF inoculation. Growth characteristics, yield components, dill essential oil percentage and intercropping efficiency indices (Land equivalent ratio, LER; Land equivalent coefficient, LEC and relative crowding coefficient, K) were analyzed.

Result: AMF inoculation significantly enhanced growth and yield of both crops and improved intercropping efficiency. All intercropping treatments recorded LER values greater than 1, confirming a clear land use advantage over sole cropping. The highest intercropping efficiency (total LER = 4.61) was observed when pinto bean was intercropped with 50% dill density under AMF inoculation. Dill essential oil concentration was also significantly increased by AMF application.

Key words: *Anethum graveolens*, Arbuscular mycorrhiza, Essential oil, Intercropping indices, *Phaseolus vulgaris*.

INTRODUCTION

Intercropping often produces higher combined yields per unit land than monoculture because mixed canopies and root systems use light, water and nutrients more efficiently. Land equivalent ratio (LER) is the standard index used to quantify this advantage, expressing the land area under sole cropping required to match intercrop yields (Mead and Willey, 1980; Ebbisa, 2022).

In legume based systems, arbuscular mycorrhizal fungi (AMF) enhance phosphorus acquisition, root development and physiological performance of common bean (*Phaseolus vulgaris* L.), leading to improved growth and yield (Ibjijsen *et al.*, 1996; Khan *et al.*, 2022). Reviews further confirm that AMF increase nutrient uptake, photosynthesis and metabolite production across crops and environments, supporting their role as low input tools for sustainable intensification (Khan *et al.*, 2022; Shukla *et al.*, 2022; Xu and Liu 2024; Souza *et al.*, 2025; Umer *et al.*, 2025; Zhou *et al.* 2025).

Dill (*Anethum graveolens* L.), an important aromatic crop, frequently responds to AMF inoculation by increasing essential oil yield and modifying terpene composition, thereby enhancing its economic value in intercropping systems (Kapoor *et al.*, 2002; Weisany *et al.*, 2015). Intercropping benefits can also be captured using complementary biological indices such as LEC and relative crowding coefficient (K) (Ghosh, 2004; Banik *et al.*, 2006; Gitaria *et al.*, 2020). Studies in Legume Research report

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consistent land use advantages (LER > 1) for optimized legume based intercropping systems (Lal *et al.*, 2014; Nawange *et al.*, 2011).

Despite these advances, integrated field studies combining AMF inoculation with additive pinto bean–dill intercropping and simultaneous assessment of yield, essential oil characteristics and economic indices under temperate semi arid conditions remain limited. This study addresses this gap.

MATERIALS AND METHODS

Experimental site and conditions

The experiment was conducted during the 2023 growing season (May-September 2023) at the Agricultural Research Farm, University of Tabriz, Iran (38.05°N, 46.17°E; 1360 m). The climate is temperate semi arid (mean annual temperature $\approx 10^{\circ}\text{C}$; max 16.6°C ; min 4.2°C). The soil at the site is classified as sandy loam, exhibiting the following characteristics (Table 1).

Experimental design and treatments

The experiment was laid out in a factorial randomized complete block design (RCBD) with three replications. Two factors were evaluated: Cropping pattern (Sole pinto bean, Sole dill, Additive intercropping of pinto bean with 25%, 50%, 75% and 100% of sole crop dill density (B:D25, B:D50, B:D75 and B:D100)) and Mycorrhizal inoculation (With arbuscular mycorrhizal fungi (AMF), Without AMF).

Each experimental plot measured 3 m $\times$ 2 m. Pinto bean was sown at a constant density of 40 plants m^{-2} , while sole dill was planted at 50 plants m^{-2} . In intercropping treatments, pinto bean density was maintained and dill density was adjusted according to treatment level. Row spacing was 50 cm for pinto bean and dill spacing was adjusted proportionally to achieve the target plant densities.

AMF inoculum and application

Arbuscular mycorrhizal fungi inoculum was obtained from the East Azerbaijan Agricultural Engineering Organization. The inoculum consisted of a mixed AMF consortium dominated by *Glomus* species, containing approximately 120-150 viable spores g^{-1} substrate, along with infected root fragments and mycelium.

AMF was applied using a seed coating method, in which pinto bean and dill seeds were moistened with water and mixed thoroughly with the inoculum immediately before sowing. Non inoculated treatments received no AMF.

Crop management and measurements

Sowing was carried out in mid May 2023. Standard agronomic practices, including irrigation and manual weed control, were applied uniformly to all plots throughout the growing season.

At physiological maturity, grain yield of both crops was recorded from the central rows of each plot to avoid border effects. Yield data from sole and intercropped treatments were used for calculating intercropping efficiency indices ($n = 10$ plants per species per plot).

Essential oil extraction (dill)

Ten plants per plot were shade dried; moisture was recorded. Seeds were ground with an electric mill. Essential oil was extracted by steam distillation using a Clevenger apparatus for 2.5 h (1 L flasks, $\sim 50\%$ distilled water). Petroleum ether was used for exhaustive extraction. Oils were stored in dark, cool, sealed vials to minimize hydrolysis/oxidation. AMF mediated enhancement of EO

yield/composition in dill has previously been reported (Kapoor *et al.*, 2002; Weisany *et al.*, 2015; Younesi *et al.*, 2020).

Intercropping indices (Standardized formulas)

Land equivalent ratio (LER) (Mead and Willey, 1980):

$$\text{LER} = \frac{\text{Yield of bean in mixture}}{\text{Yield of bean in sole}} + \frac{\text{Yield of dill in mixture}}{\text{Yield of dill in sole}}$$

(LER > 1 $\Rightarrow$ advantage).

Land equivalent coefficient (LEC):

$$\text{LEC} = \frac{\text{Yield of bean in mixture}}{\text{Yield of bean in sole}} \times \frac{\text{Yield of dill in mixture}}{\text{Yield of dill in sole}}$$

Relative crowding coefficient (K) (per species) (Gitaria *et al.*, 2020):

$$\text{Kb} = \frac{\text{Yield of bean in mixture}}{\text{Yield of bean in sole} - \text{Yield of bean in mixture}} \times \frac{\text{Zd}}{\text{Zb}}$$

$$\text{Kd} = \frac{\text{Yield of dill in mixture}}{\text{Yield of dill in sole} - \text{Yield of dill in mixture}} \times \frac{\text{Zb}}{\text{Zd}}$$

$$\text{K} = \text{Kb} \times \text{Kd}$$

Where,

Z = Sown proportions/densities; K > 1 indicates advantage.

Statistical analysis

All data were analyzed using MSTAT C statistical software (version 2.10). Analysis of variance (ANOVA) was performed to test treatment effects. Prior to ANOVA, data were examined for normality and homogeneity of variance using residual diagnostics. Treatment means were compared using Duncan's multiple range test at $P \leq 0.05$.

RESULTS AND DISCUSSION

Dill morphological traits and yield components

Analysis of variance (Table 2) showed that mycorrhizal inoculation, cropping pattern and their interaction significantly affected dill plant height, number of branches, umbels per plant, total dry weight, 1000 seed weight, biological yield, grain yield and essential oil percentage.

Mycorrhizal inoculation significantly increased dill plant height across all cropping patterns ($P \leq 0.05$) (Fig 1). Dill grown under intercropping conditions generally exhibited greater plant height than sole cropping, particularly at lower to moderate dill densities. The interaction between mycorrhiza and cropping pattern was significant ($P \leq 0.01$), indicating that the magnitude of response varied with planting configuration.

The number of secondary branches per dill plant increased significantly under AMF inoculation ($P \leq 0.05$) (Fig 2). Intercropped dill produced more branches than sole cropped dill, with the highest branching observed in AMF treated plots at higher dill densities.

Total dry biomass of dill was significantly influenced by AMF and cropping pattern ($P \leq 0.05$) (Fig 3). AMF inoculated treatments consistently recorded higher biomass values

compared with non inoculated treatments across all intercropping levels.

Seed yield and 1000 seed weight of dill were significantly enhanced by AMF application ($P \leq 0.05$) (Fig 4). Intercropped dill produced higher seed yield than sole cropping, with the greatest values observed at moderate dill densities.

Grain yield of dill was consistently higher in intercropped treatments than in sole cropping and AMF inoculation amplified this advantage (Fig 5). Across all patterns, inoculated dill produced more than twice the grain yield of non-inoculated plants.

Dill essential oil percentage

Essential oil percentage was significantly affected by AMF inoculation, cropping pattern and their interaction ($P \leq 0.05$) (Fig 6). AMF inoculated dill exhibited higher essential oil concentration than non inoculated treatments, with maximum values recorded in intercropping systems containing medium to high dill densities.

Pinto bean morphological traits and yield components

Results presented in Table 3 indicate that mycorrhizal inoculation significantly influenced pinto bean plant height, number of branches, root length, root dry weight, number

Table 1: Soil characteristics of the experimental site.

Ece $\times 10^3$	pH	P	K	Total N	OM	Sand	Silt	Clay	Texture
			Mg kg ⁻¹				%		
0.475	7.75	61	304	8	0.76	65	20	15	Sandy loam

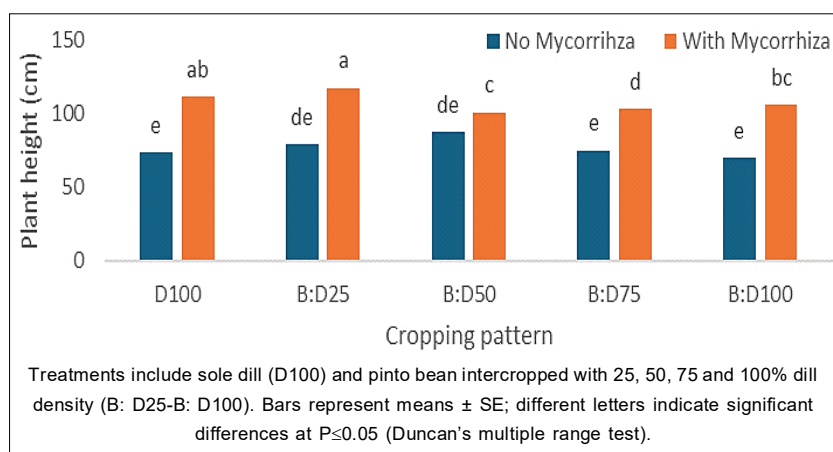


Fig 1: Effect of intercropping pattern and mycorrhizal inoculation on dill (*Anethum graveolens* L.) plant height.

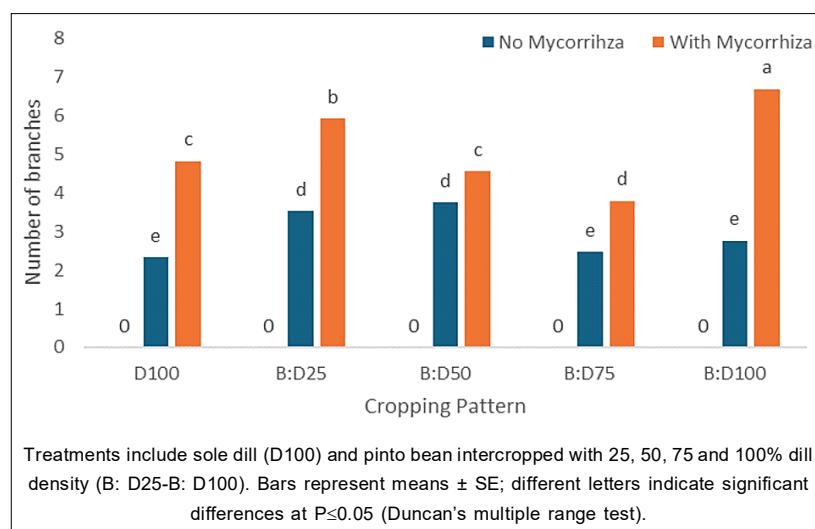


Fig 2: Effect of intercropping pattern and mycorrhizal inoculation on the number of branches per dill (*Anethum graveolens* L.) plant.

Table 2: Analysis of variance (ANOVA) for morphological traits, yield components and essential oil percentage of dill (*Anethum graveolens* L.) as influenced by intercropping pattern and mycorrhizal inoculation.

SOV	df	Plant Height	Mean squares							
			No. of branches	No of umbrellas	Total dry weight	1000 grains weight	Biological yield	Harvest index	Grain yield	Essential oil %
Rep	2	101.59*	0.183	1.23*	0.36	0.0003	2.433	30.1	2.096**	0.196
Mycorrhiza (M)	1	7195**	36.08**	8.85**	729.3**	0.012**	956.6**	1859	15.39	12.59**
Cropping (C)	4	100.6*	3.005**	1.42**	11.39*	0.0086**	13.89*	35.41	3.967**	0.948**
M × C	4	165.8**	2.19**	0.087	34.08	0.0039**	30.37	192	0.257	1.68**
Residual	18	19.45	0.189	0.247	3.47	0.00065	4.23	65.79	0.23	0.109

* and **: Significant at 5% and 1% probability levels.

Table 3: Analysis of variance (ANOVA) for morphological traits and yield components of pinto bean (*Phaseolus vulgaris* L.) as influenced by intercropping pattern and mycorrhizal inoculation.

SOV	df	Mean squares							
		Plant height	No of branches	Root length	Root dry weight	Number of seeds per plant	Biological yield	Harvest index	Grain yield
Rep	2	81.4*	2.53	0.407	0.0018*	11.03*	12.5**	13.48	756.4*
Mycorrhiza (M)	1	1059**	64.8**	234**	0.0353**	86.5**	247.7**	20.66	12280**
Cropping (C)	4	95.4*	5.19*	6.08	0.0052**	19.29**	13.47**	89.93**	2284**
M × C	4	10.39	0.138	3.768	0.0019**	7.15*	6.082*	52.01**	1008**
Residual	18	21.79	1.227	1.944	0.0001	2.371	1.86	11.31	187.2

* and **: Significant at 5% and 1% probability levels.

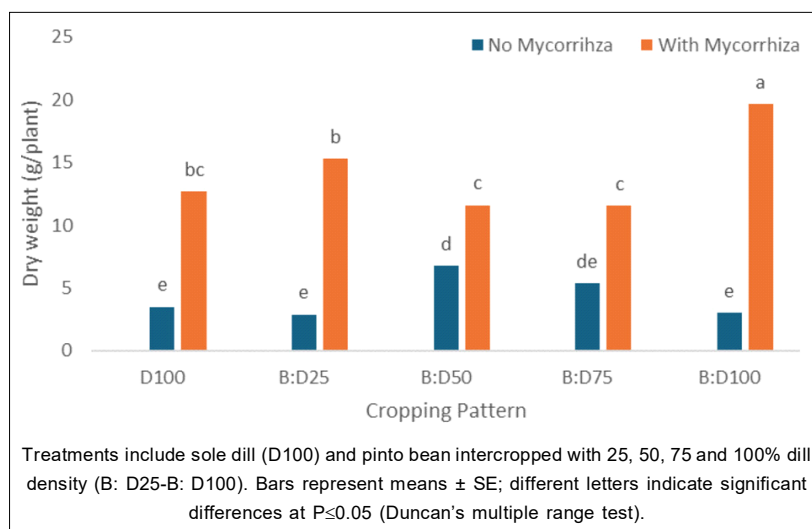


Fig 3: Effect of intercropping pattern and mycorrhizal inoculation on dry weight of dill (*Anethum graveolens* L.) plants.

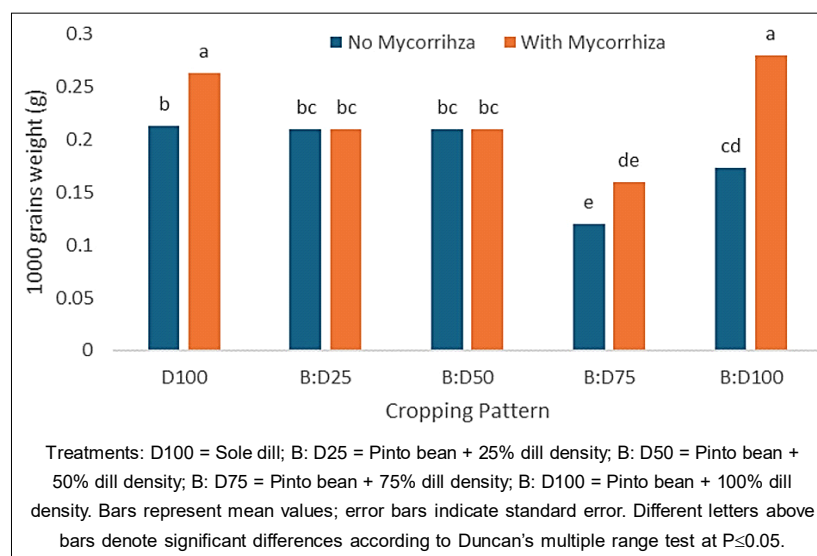


Fig 4: Effect of intercropping pattern and mycorrhizal inoculation on 1000-seed weight of dill (*Anethum graveolens* L.).

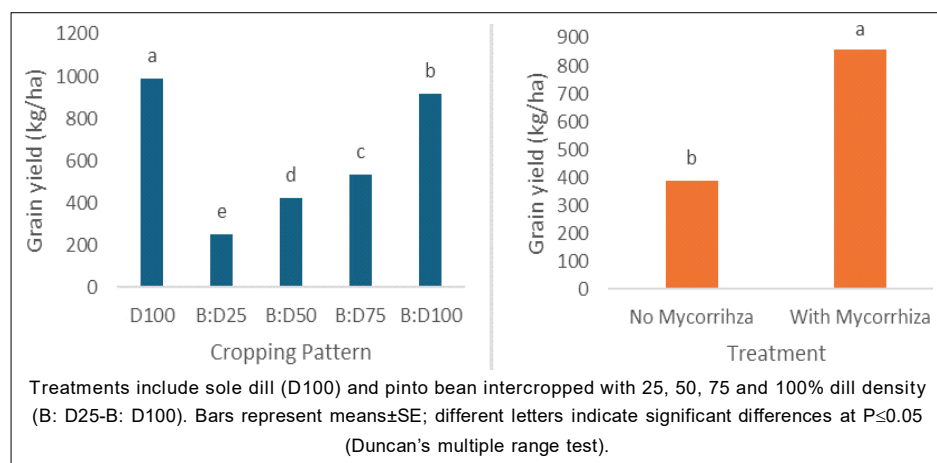


Fig 5: Effect of intercropping pattern and mycorrhizal inoculation on grain yield of dill (*Anethum graveolens* L.).

of seeds per plant, biological yield and grain yield ($P \leq 0.05$) (Table 3).

Plant height was greater in inoculated treatments across all patterns (Fig 7). Branching also improved significantly with AMF (Fig 8), with inoculated plants producing more branches than controls.

Root traits showed the most dramatic response. Root length increased substantially under AMF (Fig 9) and root dry weight nearly doubled in some intercropping patterns (Fig 10), indicating enhanced soil exploration and nutrient uptake.

Reproductive traits followed similar trends. The number of seeds per plant was higher in inoculated beans across all patterns (Fig 11) and grain yield increased significantly with AMF (Fig 12). The largest yield gains occurred in sole bean and in mixtures with low dill density, although all patterns benefited from inoculation.

Intercropping efficiency indices and economic performance

Intercropping efficiency indices for pinto bean-dill systems under mycorrhizal inoculated and non inoculated conditions are presented in Table 4.

All intercropping treatments recorded total land equivalent ratio (LER) values greater than 1, indicating a clear land use advantage of intercropping compared with sole cropping. The highest total LER (4.61) was observed in pinto bean intercropped with 50% dill density under AMF inoculation.

Component LER values showed that both pinto bean and dill contributed positively to total LER in intercropping systems. LER values for both crops were consistently higher in AMF inoculated treatments than in non inoculated treatments, particularly at moderate dill densities.

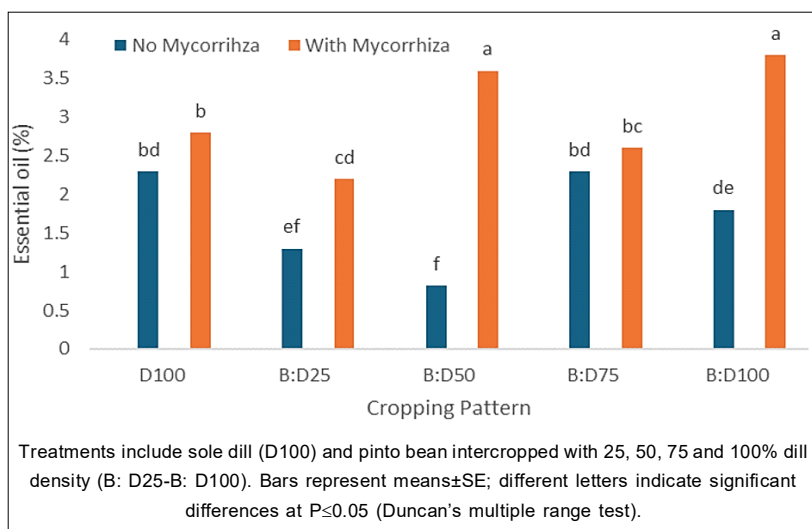


Fig 6: Effect of intercropping pattern and mycorrhizal inoculation on essential oil percentage in dill (*Anethum graveolens* L.) seeds.

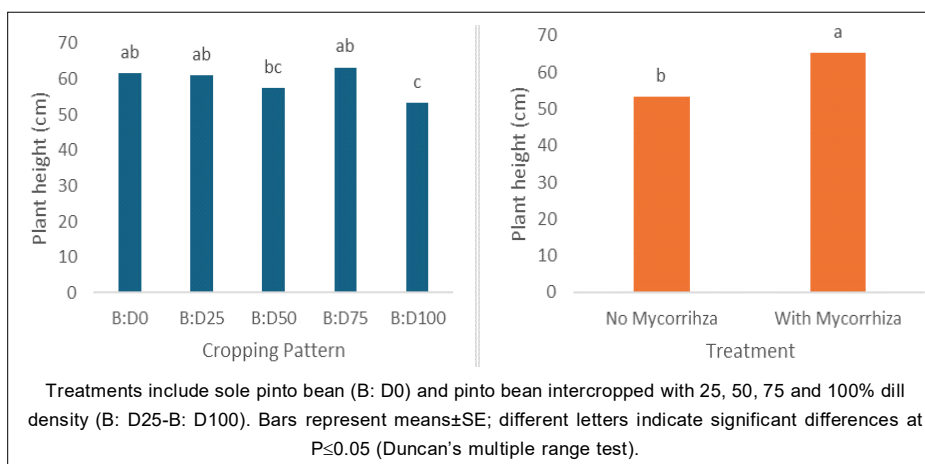


Fig 7: Effect of intercropping pattern and mycorrhizal inoculation on plant height of pinto bean (*Phaseolus vulgaris* L.).

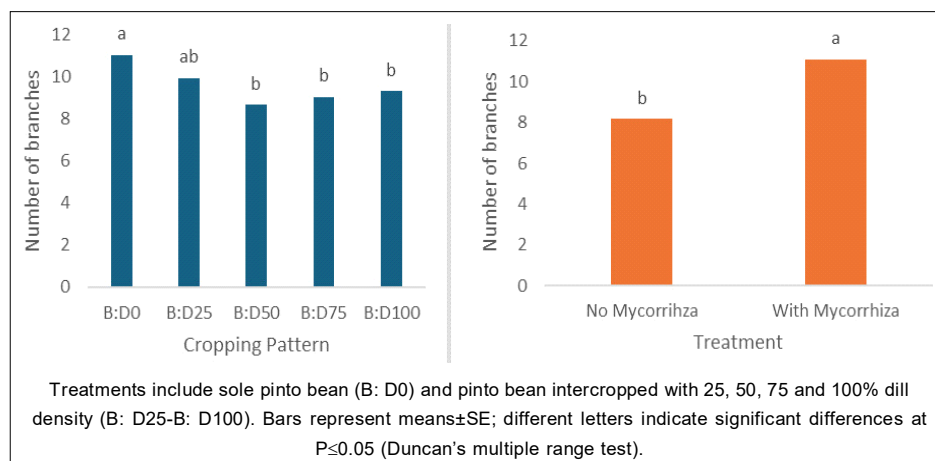


Fig 8: Effect of intercropping pattern and mycorrhizal inoculation on the number of branches per pinto bean (*Phaseolus vulgaris* L.) plant.

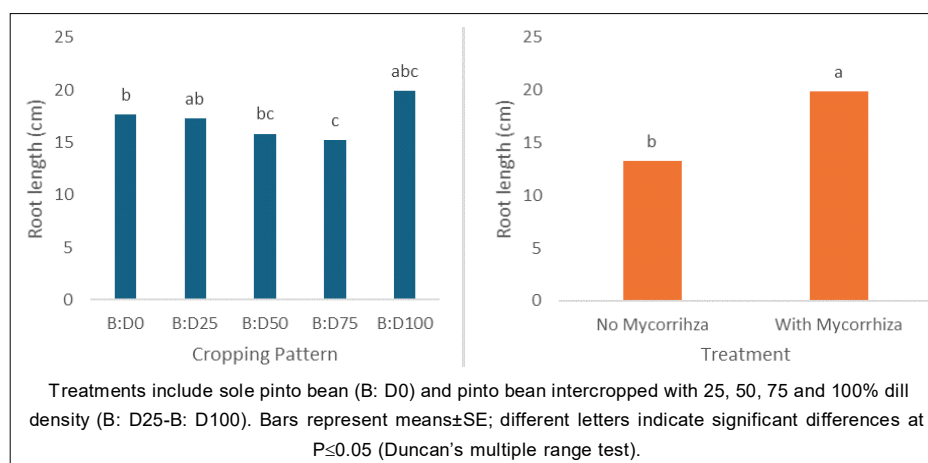


Fig 9: Effect of intercropping pattern and mycorrhizal inoculation on root length of pinto bean (*Phaseolus vulgaris* L.).

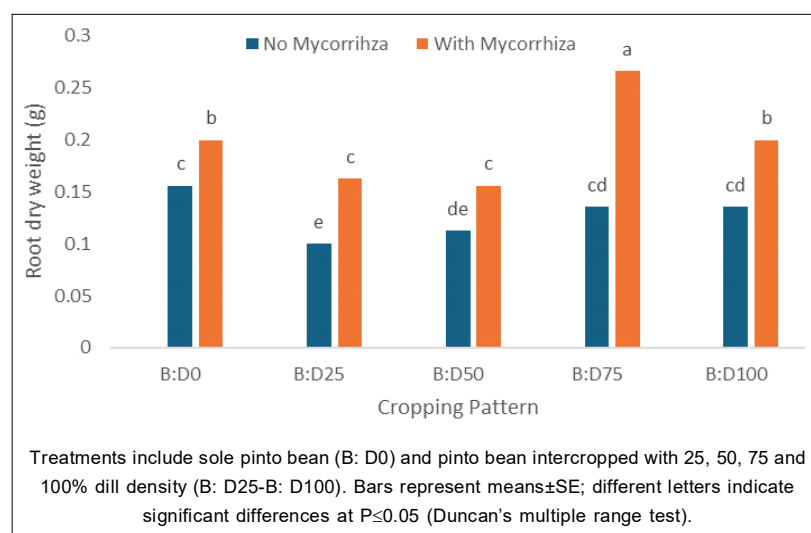


Fig 10: Effect of intercropping pattern and mycorrhizal inoculation on root dry weight of pinto bean (*Phaseolus vulgaris* L.).

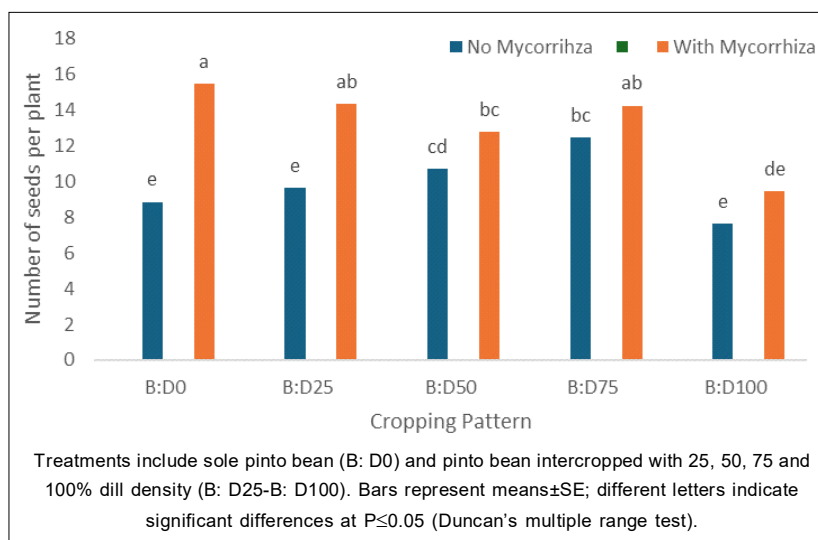


Fig 11: Effect of intercropping pattern and mycorrhizal inoculation on number of seeds per plant of pinto bean (*Phaseolus vulgaris* L.).

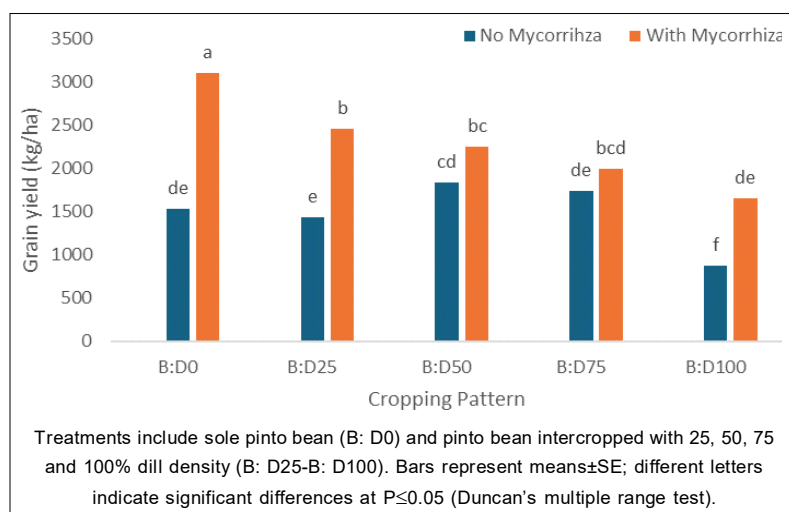


Fig 12: Effect of intercropping pattern and mycorrhizal inoculation on grain yield of pinto bean (*Phaseolus vulgaris* L.).

Table 4: Intercropping efficiency and economic indices of pinto bean (*Phaseolus vulgaris* L.) and dill (*Anethum graveolens* L.) as affected by cropping pattern and AMF inoculation.

AMF treatment	Cropping pattern	LER (Bean)	LER (Dill)	Total LER	LEC	K
AMF	B: D25	1.60 ^b	1.83 ^a	3.42 ^{bc}	2.93 ^c	4.63 ^a
AMF	B: D50	1.49 ^{bc}	3.12 ^a	4.61 ^a	4.63 ^a	5.26 ^{de}
AMF	B: D75	1.31 ^{bd}	2.29 ^a	3.60 ^{bc}	2.993 ^{bc}	3.61 ^{bc}
AMF	B: D100	1.07 ^{de}	2.01 ^a	3.08 ^{cd}	2.166 ^{cd}	3.08 ^{cd}
No AMF	B: D25	0.92 ^{le}	1.02 ^a	1.94 ^e	0.923 ^{ef}	1.95 ^e
No AMF	B: D50	1.21 ^{oe}	1.93 ^a	3.14 ^{cd}	2.34 ^{cd}	3.14 ^{cd}
No AMF	B: D75	1.13 ^{de}	1.60 ^a	2.74 ^d	1.813 ^{de}	2.74 ^d
No AMF	B: D100	0.58 ^f	1.45 ^a	2.03 ^e	0.846 ^f	2.03 ^e

B: D25, B: D50, B: D75 and B: D100 represent additive intercropping of pinto bean with 25%, 50%, 75% and 100% of sole crop dill density, respectively. LER= Land equivalent ratio; LEC= Land equivalent coefficient; K= Relative crowding coefficient. Values followed by different superscript letters within a column differ significantly at $P \leq 0.05$ according to Duncan's multiple range test.

Land equivalent coefficient (LEC) values exceeded the threshold value of 0.25 in most intercropping treatments, confirming a biological yield advantage of component crops grown together. Higher LEC values were consistently recorded under AMF inoculation, with the maximum value observed in the pinto bean + 50% dill density treatment.

Relative crowding coefficient (K) values were greater than unity in all AMF inoculated intercropping treatments, indicating competitive dominance and more efficient resource utilization in these systems. In contrast, lower K values were recorded in non inoculated treatments, reflecting reduced intercropping efficiency in the absence of mycorrhizal inoculation.

Summary of treatment effects

Overall, AMF inoculation improved plant height, branching, root development, seed components, biomass, essential oil percentage and final yields in both species. Cropping pattern influenced the magnitude of these responses, with moderate dill density in mixtures providing the best balance between resource sharing and competition. The interaction between AMF and cropping pattern was significant for several traits, highlighting the importance of optimizing both biological and management factors. The combined analysis of growth, yield, quality and intercropping indices identifies bean plus 50% dill with AMF as the most productive and profitable configuration.

The present study demonstrates that arbuscular mycorrhizal fungi (AMF) markedly enhance the efficiency of pinto bean-dill intercropping systems under temperate semi arid conditions. Improvements in intercropping performance were consistently reflected by higher total and component land equivalent ratio (LER) values, land equivalent coefficient (LEC) and relative crowding coefficient (K) in AMF inoculated treatments compared with non inoculated systems.

The consistently higher total LER values under AMF inoculation indicate improved land use efficiency relative to sole cropping. In particular, the maximum total LER observed at moderate dill density (50%) suggests optimal complementarity between pinto bean and dill when supported by mycorrhizal symbiosis. This finding supports the concept that AMF enhance niche differentiation and resource partitioning among component crops, resulting in more effective utilization of soil nutrients and growing space (Mead and Willey, 1980; Meng *et al.*, 2015; Zampieri *et al.* 2024; Veršulienė *et al.*, 2025).

Elevated LEC values in AMF treated plots further confirm the biological advantage of intercropping systems. Since LEC values exceeding 0.25 indicate efficient combined productivity, the higher LEC recorded under AMF inoculation demonstrates that both pinto bean and dill

actively contributed to yield advantage rather than one crop dominating the system. This outcome highlights the role of AMF in strengthening facilitative interactions between legume and non legume crops.

Relative crowding coefficient (K) values greater than unity in AMF inoculated treatments indicate improved competitive balance and enhanced resource use efficiency within intercropping systems. Higher K values suggest that AMF mitigated interspecific competition by improving root growth and nutrient acquisition, particularly phosphorus, which is a key limiting factor for legume productivity (Ibjijsen *et al.*, 1996; Khan *et al.*, 2022).

The improved performance of dill within intercropping systems under AMF inoculation can be attributed to enhanced nutrient availability and physiological efficiency. Previous studies have shown that AMF positively influence growth and quality traits of aromatic crops, including dill, through improved nutrient uptake and enhanced secondary metabolite synthesis (Kapoor *et al.*, 2002; Weisany *et al.*, 2015). These mechanisms likely contributed to the stronger contribution of dill to total LER in AMF inoculated treatments.

The results of this study are consistent with findings reported in ARCC journals, where legume based intercropping systems frequently achieved LER values greater than unity, confirming both agronomic and land use advantages under diverse management conditions (Lal *et al.*, 2014; Nawange *et al.*, 2011).

CONCLUSION

Arbuscular mycorrhizal fungi substantially improve the efficiency of pinto bean-dill intercropping systems under temperate semi arid field conditions. AMF inoculation increased land use efficiency, as evidenced by higher total and component LER values, enhanced LEC and greater relative crowding coefficient (K), indicating improved complementarity and resource utilization between component crops.

Among the intercropping configurations evaluated, pinto bean intercropped with 50% dill density under AMF inoculation emerged as the most efficient system, achieving the highest intercropping advantage. These findings demonstrate that integrating AMF into legume-aromatic intercropping systems can enhance productivity and sustainability in low input agroecosystems.

Overall, AMF assisted pinto bean-dill intercropping represents a promising agronomic strategy for improving land use efficiency and crop interactions in temperate semi arid regions.

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Authors' contributions

Saeid Zehtab Salmasi: Conceptualization, writing, supervision; Saba Dadashzadeh Bonab: methodology, data collection, analysis; Yagoub Raei: conceptualization, supervision.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Ethic

This study involved plants only; no human or animal subjects.

Funding

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Informed consent

This study involved plants only; no human or animal subjects. Informed consent is not applicable.

Conflict of interest

The authors declare no competing interests.

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