



Intercropping of Cowpea and Buckwheat: A Sustainable Strategy for Higher Yield and Weed Suppression Under Water Deficit

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Abstract

Enhancing water productivity and weed control through intercropping is critical for sustainable production in semi-arid regions. A two-year field study (2022–2023) evaluated the combined effects of irrigation level, planting pattern, and weed-control duration on buckwheat (*Fagopyrum esculentum*) and cowpea (*Vigna unguiculata*). Treatments included three irrigation regimes (100%, 85%, and 70% of crop water requirement), five planting patterns (100B, 100 C, 75B–25 C, 50B–50 C, and 25B–75 C), and five weed-control durations (0–8 weeks after sowing). Significant triple interactions ($p < 0.05$) were found for grain yield, biomass, irrigation water productivity (IWP), weed biomass, and land equivalent ratio (LER). Buckwheat and cowpea monocultures yielded up to 2397 and 1316 kg ha⁻¹ under full irrigation with eight weeks of weed control, while the 50B–50 C intercrop maintained higher yield stability and weed suppression under deficit irrigation. IWP peaked at 0.57 kg ha⁻¹ mm⁻¹ for buckwheat and 0.46 kg ha⁻¹ mm⁻¹ for the 50B–50 C intercrop. Weed biomass declined sharply within four weeks of control, and species such as *Amaranthus retroflexus* density was reduced by more than 50% in intercrops. The 50B–50 C pattern consistently achieved land equivalent ratio (LER) > 1.0 across irrigation levels. Artificial neural network modeling ($R^2 = 0.87–0.92$) accurately predicted vertical biomass distribution, emphasizing the strong influence of irrigation and weed control on canopy structure. Overall, balanced intercropping (50B–50 C) combined with moderate deficit irrigation (85%) and at least six weeks of weed control optimized yield, water productivity, and weed suppression in semi-arid conditions.

Keywords Intercropping · Buckwheat · Cowpea · Deficit irrigation · Planting patterns · Weed suppression

Introduction

Intercropping, the simultaneous cultivation of two or more crop species on the same land, is a sustainable agricultural practice that enhances environmental health and promotes resilient farming systems (Thierfelder & Mhlanga, 2022; Nyaupane et al., 2023). Its benefits are especially relevant

in arid and semi-arid regions, where water scarcity and low soil fertility constrain production. In such environments, intercropping drought-resilient species with complementary traits can increase IWP, reduce soil erosion, and improve soil organic matter and moisture retention (Yin et al., 2020; Glaze-Corcoran et al., 2020). In addition, it improves soil structure and fertility, enhances IWP, and provides natural weed suppression through canopy shading, competitive interactions, and, in some cases, allelopathic effects (Bogati & Walczak, 2022; Glaze-Corcoran et al., 2020; Sharma et al., 2021). These ecological benefits contribute to the stability and resilience of agroecosystems, enabling them to better withstand stresses such as drought, nutrient limitations, and climate variability (Abou El-Enin et al., 2023). Consequently, intercropping represents a key strategy for developing productive, environmentally friendly, and long-term sustainable farming systems.

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Under water-limited conditions, priority should be given to drought-tolerant species or combinations that exploit different soil layers for water capture. Strategic pairing of shallow- and deep-rooted crops, or species with contrasting water-use strategies, improves soil moisture utilization and overall water-use efficiency (Yin et al., 2020). Thoughtful crop selection not only maximizes yields under stress but also strengthens system resilience, maintains soil health, and preserves ecological balance.

One of the most important ecological advantages of intercropping is its ability to suppress weeds. By combining crops with diverse growth habits, canopy architectures, and rooting patterns, intercropping systems occupy a larger proportion of available resources—light, water, and nutrients—thereby limiting opportunities for weed establishment and growth (Gu et al., 2021; Sharma et al., 2021). Dense or multilayered canopies also limit light penetration, thereby suppressing weed emergence, growth and competitiveness against crops (Bilalis et al., 2010; Farooq et al., 2019).

Cowpea (*Vigna unguiculata* L. Walp.) and buckwheat (*Fagopyrum esculentum* Moench) are particularly promising candidates for intercropping systems in semi-arid and water-limited environments. Cowpea is a drought-tolerant legume with high nutritional and economic value; it contributes to soil fertility through biological nitrogen fixation, provides prolonged ground cover, and maintains productivity under limited moisture (Omomowo & Babalola, 2021; Cuartero et al., 2022). Buckwheat grows rapidly, establishes a dense canopy, and is well adapted to marginal soils, contributing to weed suppression and IWP (Arduini et al., 2016; Martínez-Goñi et al., 2023). Buckwheat yields typically 405 to 2725 kg ha⁻¹ under normal conditions, with an average of approximately 900 kg ha⁻¹ in rainfed systems. It exhibits strong drought resilience due to physiological traits such as stomatal regulation and the accumulation of photoprotective compounds. These characteristics make buckwheat an economically viable crop for water-scarce regions (Rangappa et al., 2023; Rotili et al., 2023). Their complementary traits—shallow versus deep rooting and rapid versus sustained canopy development—allow efficient resource partitioning, reduce interspecific competition, and enhance overall system resilience (Adu et al., 2019; Arvin et al., 2024).

Although intercropping buckwheat with legumes such as fenugreek or soybean has been explored, research on buckwheat–cowpea combinations remains limited, particularly under water-deficit conditions. Few studies have investigated their joint performance with respect to optimal planting ratios, irrigation water productivity, canopy structure, and weed suppression. This knowledge gap is especially significant in semi-arid regions where water scarcity and weed pressure challenge sustainable crop production. The novelty of this study lies in its systematic evaluation

of buckwheat–cowpea intercropping under deficit irrigation, integrating both agronomic and ecological outcomes, including yield, weed suppression, canopy architecture, and the LER.

Key research questions guiding this study include: Which planting ratios maximize grain yield and irrigation water productivity? How can canopy structure be managed to suppress weeds while minimizing interspecific competition? We hypothesize that intercropping buckwheat with cowpea enhances both yield and water productivity compared to monocultures, owing to complementary growth traits, optimized canopy architecture, and effective weed suppression. To test this hypothesis, the study evaluates different planting patterns under deficit irrigation and assesses canopy characteristics, weed dynamics, and system performance under varying durations of weed competition and drought stress. This approach provides insights into the ecological and agronomic potential of buckwheat–cowpea intercropping in semi-arid, water-limited environments.

Materials and methods

The study was conducted during 2022 and 2023 at the research farm of the Faculty of Agriculture, University of Tehran, Karaj, Iran (Fig. 1 for geographical coordinates), a semi-arid region with mean annual rainfall of 247 mm and mean temperature of 14.4 °C (−20 to 42 °C). Soil characteristics (0–30 cm) are presented in Table 2.

Experimental Design

A split–split plot design in a randomized complete block with three replications was used. Main plots were three irrigation regimes: full irrigation (100%), 85%, and 70% of crop water requirement. Subplots included five planting patterns: buckwheat monoculture (100B), cowpea monoculture (100 C), alternating rows of buckwheat (50) and cowpea (50) (50B–50 C), three rows of buckwheat (75) with one row of cowpea (25) (75B–25 C), and one row of buckwheat (25) with three rows of cowpea (75) (25B–75 C). Sub-subplots were five weed-control durations: no weeding, and weed-free for the first 2, 4, 6, or 8 weeks after sowing.

Plots measured 4 × 5 m with six rows each (four central rows sampled, two border rows discarded). Plant density was 120 plants m⁻² for buckwheat and 20 plants m⁻² for cowpea, with 50 cm row spacing. No fertilizers, herbicides, or pesticides were applied. Both crops were sown on May 26 and harvested on September 10 in both years.

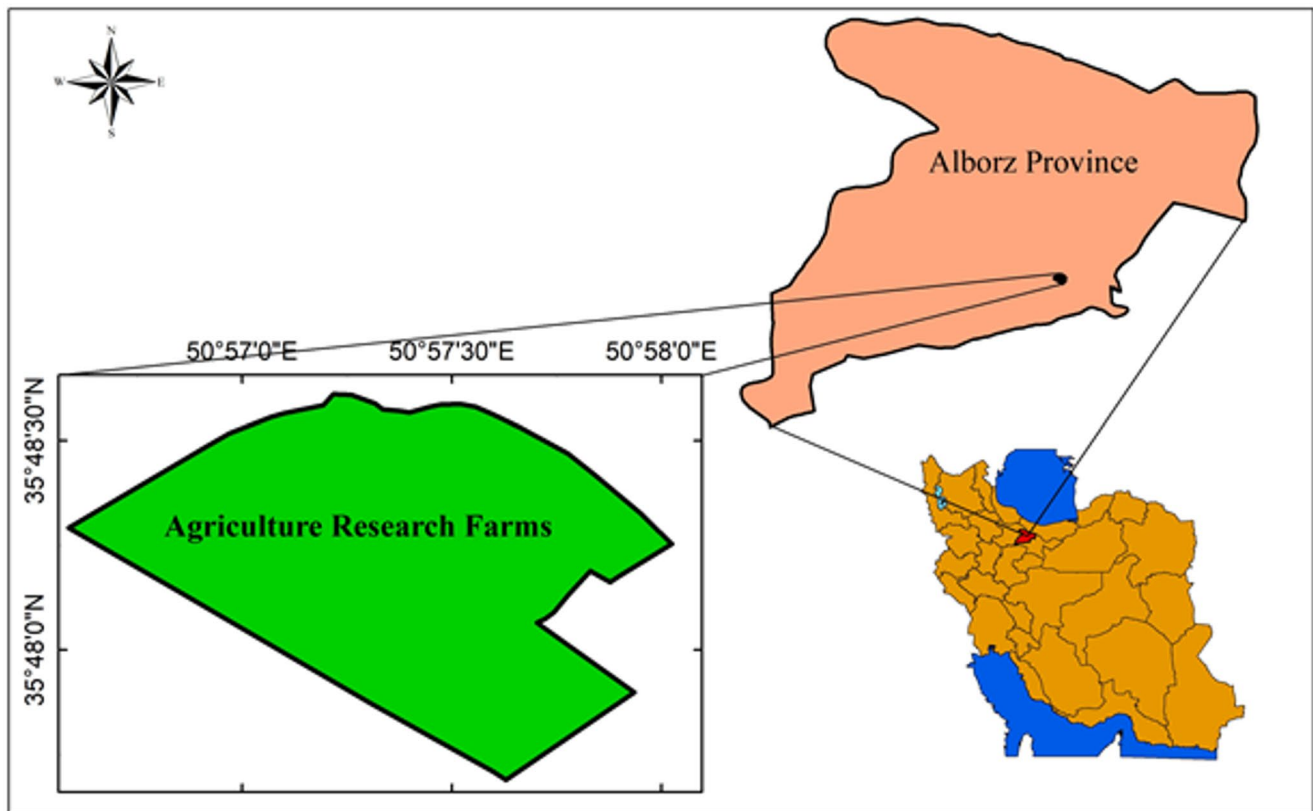


Fig. 1 Geographical location of the research area in Karaj, Alborz Province, Iran, indicating the experimental farm and its GPS coordinates (latitude: 35.48°, longitude: 50.57°)

Table 1 Physical and chemical properties of the soil at the experimental site (0–30 cm depth)

Potassium (mg kg ⁻¹)	Phosphorus (mg kg ⁻¹)	Total Nitrogen (%)	Texture soil	Organic matter (%)	pH	EC _e (dS.m ⁻¹)
194	12.4	0.076	Clay Loam	0.65	7.71	0.96

Table 2 Mean population size and standard deviation (SD) of the dominant weed species observed under different treatments

Irrigation	Planting Pattern	Amaranthus retroflexus	Convolvulus arvensis	Tribulus terrestris	Heliotropium europaeum	Chenopodium album
100	100 C	10.6 ^a (±1.5)	2.3 ^b (±0.5)	2.3 ^a (±0.5)	1.3 ^{de} (±0.5)	3.3 ^a (±0.5)
	25B-75 C	7 ^b (±1)	1 ^{de} (±0)	1.3 ^{bcd} (±0.5)	2.3 ^{bc} (±0.5)	1.6 ^b (±0.5)
	50B-50 C	4.6 ^{cd} (±1.1)	2 ^{bc} (±0)	1.6 ^{bc} (±0.5)	1.6 ^{cd} (±0.5)	1 ^{bcd} (±1)
	75B-25 C	3.3 ^{def} (±0.5)	3.3 ^a (±0.5)	1.3 ^{bcd} (±0.5)	1.3 ^{de} (±1.1)	0.3 ^{cd} (±0.5)
	100B	7.6 ^b (±1.5)	0.6 ^e (±0.5)	2 ^{ab} (±1)	0.6 ^{ef} (±0.5)	1.6 ^b (±0.5)
85	100 C	6 ^{bc} (±1.7)	2.3 ^b (±0.5)	1.3 ^{bcd} (±0.5)	2.3 ^{bc} (±1.5)	3.3 ^a (±0.5)
	25B-75 C	5 ^{cd} (±1)	0.6 ^e (±0.5)	0.6 ^{def} (±0.5)	2.6 ^b (±0.5)	1 ^{bcd} (±1)
	50B-50 C	3.3 ^{ef} (±0.5)	0.6 ^e (±0.5)	0 ^f (±0)	2.3 ^{bc} (±0.5)	1.3 ^{bc} (±0.5)
	75B-25 C	2.3 ^{ef} (±0.5)	1 ^{de} (±0)	0 ^f (±0)	1.6 ^{cd} (±0.5)	1 ^{bcd} (±0)
	100B	3.6 ^{def} (±0.5)	1.3 ^{cde} (±0.5)	0.3 ^{ef} (±0.5)	0.3 ^f (±0.5)	1.6 ^b (±0.5)
70	100 C	4.3 ^{cd} (±1.1)	2.3 ^b (±0.5)	1 ^{cde} (±0)	3.3 ^a (±1.5)	1 ^{bcd} (±1)
	25B-75 C	4 ^{de} (±1)	1.6 ^{bcd} (±0.5)	0 ^f (±0)	1.6 ^{cd} (±1.1)	0.3 ^{cd} (±0.5)
	50B-50 C	2.3 ^{ef} (±0.5)	0.6 ^e (±0.5)	0.6 ^{def} (±0.5)	0.6 ^{ef} (±0.5)	0 ^d (±0)
	75B-25 C	2 ^f (±1)	1.6 ^{bcd} (±0.5)	0 ^f (±0)	1.3 ^{de} (±0.5)	0 ^d (±0)
	100B	4.3 ^{cd} (±0.5)	0.6 ^e (±1.1)	1.6 ^{bc} (±0.5)	1 ^{de} (±1)	0.6 ^{bcd} (±0.5)

Different lowercase letters within the same column indicate significant differences among treatments based on the LSD test ($P < 0.05$)

Irrigation Management

Irrigation requirements were calculated using the FAO-56 Penman–Monteith method (Allen et al., 1998), crop evapotranspiration was calculated as follows (Eq. (1)):

$$ET_c = K_c \times ET_o \quad (1)$$

where ET_c is the crop evapotranspiration (mm day^{-1}), K_c is the crop coefficient and ET_o is the reference evapotranspiration (mm day^{-1}). Crop evapotranspiration was calculated using CROPWAT 8.0, a software developed by the FAO (Smith, 1992).

Crop coefficients (K_c) for cowpea (0.5, 1.05, 0.35) and buckwheat (0.58, 1.1, 0.74) were adjusted for local conditions using the FAO correction formula (Allen et al., 1998; Yan et al., 2015).

Since crop coefficients are generalized values, they were further adjusted to local climatic conditions using the correction formula implemented in CROPWAT 8.0 (Eq. (2)):

$$K_{cmid} = K_{cmid}(Tab) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](h/3)^{0.3} \quad (2)$$

where $K_{cmid}(Tab)$ refers to the plant coefficient value, u_2 is the average daily wind speed at a height of two meters (m s^{-1}), RH_{min} is the average daily minimum relative humidity (%), and h represents the average plant height (m). For intercrops, mean K_c values were applied following FAO recommendations for species of similar height and canopy structure.

Deficit irrigation (85% and 70%) was applied from BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) 12 (establishment) to BBCH 85–86 (maturity).

Daily meteorological data including minimum and maximum temperatures, minimum, maximum and mid relative humidity, average wind speed, net radiation and precipitation were taken from the meteorological station located at the experimental field during the growing season. Figure. 2 illustrates the meteorological conditions throughout the 2022 and 2023 growing seasons, encompassing maximum and minimum temperatures (T_{max} and T_{min} , $^{\circ}\text{C}$), evaporation rate (Eva, mm), relative humidity (RH, %), and rainfall (mm).

Soil moisture was monitored before and after irrigation in all treatments using gravimetric sampling and TDR at depths of 0–20, 20–40, and 40–60 cm to validate the accuracy of the applied irrigation volumes. These measurements confirmed that the intended water deficits of 85% and 70% of full irrigation were consistently achieved across treatments, with soil water content in the root zone reflecting the intended irrigation levels.

The irrigation time for full irrigation (100%) was calculated using the formula (Eq. (3)) (Harisha et al., 2023):

$$T = (A \times ET_c \times 60 \times Eff) / (n \times q) \quad (3)$$

where T is irrigation time (min), A is the wetted area per plot (m^2) covered by the drip laterals, ET_c is the crop evapotranspiration (mm day^{-1}), Eff is the irrigation system efficiency, n is the number of emitters, and q is the emitter discharge

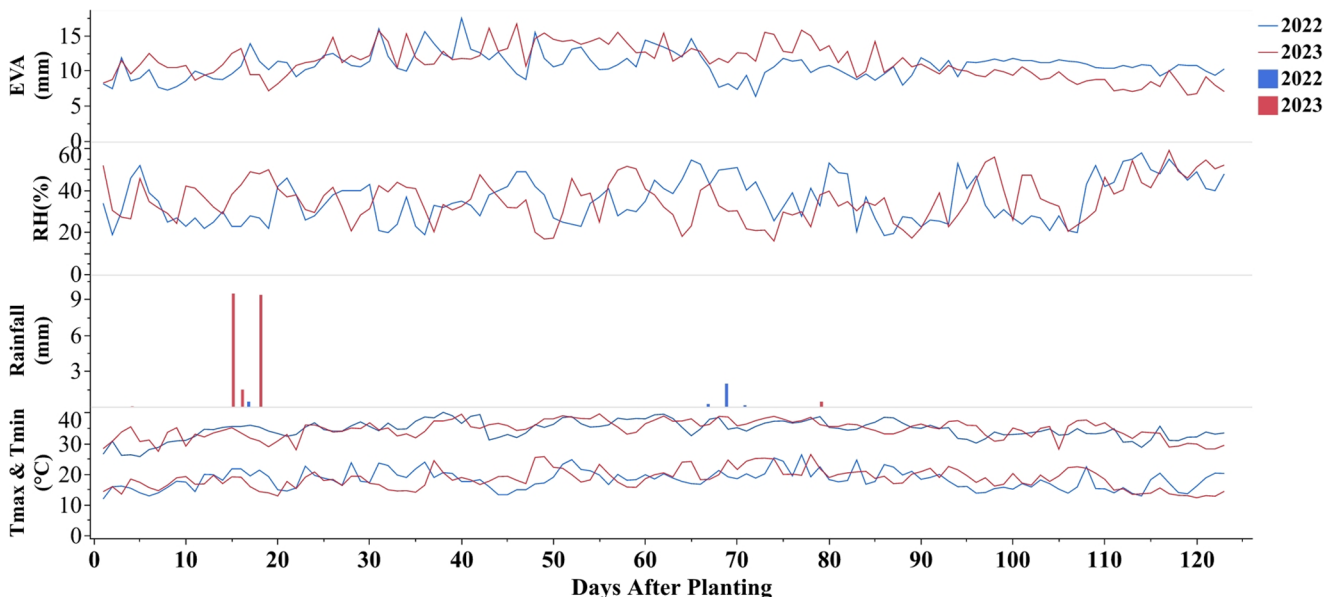


Fig. 2 Meteorological data recorded during the 2022 and 2023 growing seasons, including maximum temperature (T_{max} , $^{\circ}\text{C}$), minimum temperature (T_{min} , $^{\circ}\text{C}$), evaporation rate (Eva, mm), relative humidity (RH, %), and rainfall (mm)

(L/h). For the deficit irrigation treatments (85% and 70%), the irrigation duration and water volume were adjusted as percentages of the full irrigation treatment, accounting for system efficiency to ensure accurate water application. Irrigation was applied every 4 days using a surface drip irrigation system with 16-mm polyethylene lateral pipes, equipped with emitters spaced 10 cm apart, each delivering 1.2 L h⁻¹. Filtration was managed with a mesh filter, and water volume was regulated by a flow meter. Seasonal water applied under 100% irrigation was 426 mm in 2022 and 461 mm in 2023, with proportional reductions for deficit treatments. These totals correspond to 24 scheduled irrigation events each season, resulting in mean application depths of 17.8 mm in 2022 and 19.2 mm in 2023. The reported depths are expressed as whole-plot equivalents (mm over the entire plot area). Volumes were precisely controlled using flow meters, ensuring negligible variability across replications.

Crop and Weed Sampling

Weed biomass was recorded before harvest in all treatments. Sampling for vertical biomass distribution was conducted at BBCH 51 using a 50 × 50 cm quadrat, with biomass separated into 20 cm canopy layers (0–140 cm). Weeds were oven-dried at 75 °C for 48 h. Crop yield was measured from an 8 m² area (excluding borders) and harvested at BBCH 85–89 for both species.

Calculations

Estimation of irrigation water productivity.

IWP was calculated as grain yield (kg ha⁻¹) per unit irrigation water applied (mm) (Eq. (4)). For intercrops, yields of both species were summed (Chen et al., 2018).

$$IWP = Yd/I \quad (4)$$

IWP is in kg ha⁻¹ mm⁻¹, *Yd* is the crop yield per unit area (kg ha⁻¹), and *I* the total irrigation water applied (mm).

Determination of Weed Species

Weed community composition was assessed using the Importance Value Index (IVI) based on relative density and frequency (Mueller-Dombois & Ellenberg, 1974).

Indices calculation

To describe the response of crop grain yield and biomass to the experimental factors, we fitted a second-order (quadratic) polynomial regression model (Eq. (5)):

$$p(x) = ax^2 + bx + c \quad (5)$$

where *p(x)* represents the predicted grain yield (kg ha⁻¹) or biomass (kg ha⁻¹), and *x* is the duration of the weed-free period (weeks after planting), *a*, *b*, and *c* are the model coefficients.

To characterize the change in weed biomass over increasing weed-free periods, we fitted a third-order (cubic) polynomial regression (Eq. (6)):

$$p(x) = ax^3 + bx^2 + cx + d \quad (6)$$

where *p(x)* represents the predicted weed biomass (g m⁻²), and *x* is the duration of the weed-free period (weeks after planting), *a*, *b*, *c*, and *d* are the model coefficients.

The land equivalency ratio (LER) was calculated using the following formula (Eq. (7)):

$$LER = (Y_{ab}/Y_a) + (Y_{ba}/Y_b) \quad (7)$$

Y_{ab} is the yield of plant *a* in intercropping, *Y_a* is the yield of plant *a* in monoculture, *Y_{ba}* is the yield of plant *b* in intercropping, and *Y_b* is the yield of plant *b* in monoculture.

To evaluate the economic advantage of the intercropping system, the Monetary Advantage Index (MAI) was calculated using the following formula (Ghosh, 2004) (Eq. (8)):

$$MAI = (\text{Value of combined intercrops}) \times \left(\frac{LER - 1}{LER} \right) \quad (8)$$

Value of combined intercrops is the sum of the yields of each crop (in kg per hectare) multiplied by their respective global prices (in USD/kg), and *LER* is the Land Equivalent Ratio. For the economic analysis, international average market prices were applied: buckwheat at 1.985 USD/kg (www.selinawamucii.com) and cowpea at 1.750 USD/kg (www.tridge.com).

The De Martonne Aridity Index (*AI*) was calculated to assess the climatic conditions of the study area in Karaj, Iran, using the following formula (Eq. (9)):

$$AI = P/(T + 10) \quad (9)$$

where *P* is the mean annual precipitation and *T* is the mean annual temperature (Kouchak et al., 2023). Long-term meteorological data were used to derive the *AI* value.

Artificial Neural Network (ANN) Modeling

An ANN was developed in JMP Pro 17.0 to predict vertical biomass distribution. Inputs included irrigation level, weed-control duration, planting pattern, canopy layer, and

crop species, the output was biomass per layer. Data were split into training (50%), validation (25%), and test (25%) subsets. Model performance was evaluated by R^2 , RMSE, and MAE. Detailed architecture and hyperparameters are provided in Table 2.

Statistical Analysis

Data were analyzed using Linear Mixed Models (LMM) in JMP Pro 17.0 with irrigation (I), planting pattern (P), and weed-control duration (W) as fixed effects, and block and year as random effects (Eq. (10)):

$$Y = \mu + I + P + W + I \times P + I \times W + P \times W + I \times P \times W + (1 | \text{Block}) + (1 | \text{Year}) + \varepsilon \quad (10)$$

where Y represents the outcome (grain yield, biomass, weed biomass, LER, or IWP), μ is the grand mean, $I \times P$, $I \times W$, $P \times W$, and $I \times P \times W$ denote the full factorial interactions of fixed effects, $(1 | \text{Block})$ and $(1 | \text{Year})$ indicate random intercepts for block and year, and ε is the residual error.

Normality and variance homogeneity were tested with Shapiro–Wilk and Bartlett’s tests. Regression models were used for visualization; mean separations were performed using protected LSD at $p < 0.05$.

Results

The mixed-model ANOVA revealed significant interactions between planting patterns, irrigation regimes, and weed-control timing across all measured traits, including grain yield, biomass, IWP, weed biomass, and LER. The De Martonne’s Aridity Index (AI) for Karaj was calculated as 10.24, confirming semi-arid conditions. This index supported the water deficit context of the study.

Grain Yield of Buckwheat and Cowpea

Grain yield varied substantially with irrigation, planting pattern, and weed-control duration (Fig. 3). Under full irrigation, buckwheat monoculture with eight weeks of weed control achieved the highest yield (2397 kg ha⁻¹), whereas cowpea monoculture reached 1316 kg ha⁻¹. At 85% irrigation, buckwheat monoculture with six weeks of weed control yielded 1801 kg ha⁻¹, and cowpea monoculture 1182 kg ha⁻¹. Under 70% irrigation, yields for buckwheat and cowpea monocultures were 1616 and 962 kg ha⁻¹, respectively, with no significant difference between six- and eight-week weed-control treatments.

Among intercropping patterns, the 50B–50 C ratio consistently outperformed 75B–25 C and 25B–75 C, particularly under deficit irrigation with early weed control (0–4 weeks). Cowpea grain yield was generally less sensitive to early weed control, though irrigation effects were significant across all intercropping ratios. Yield reductions due to

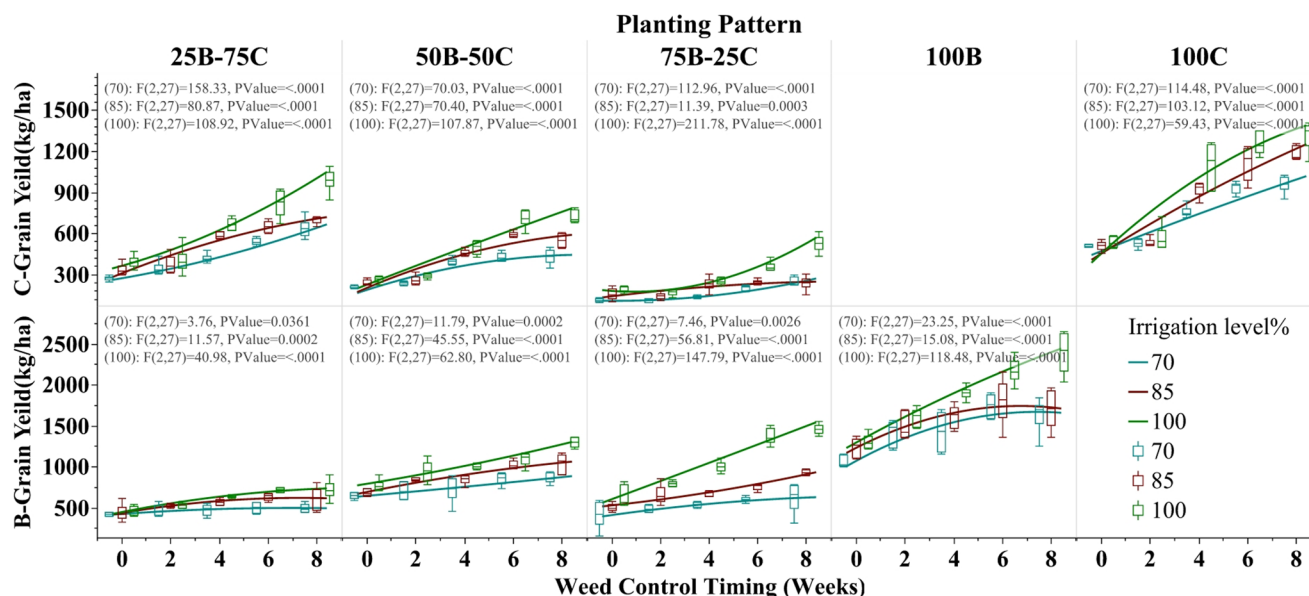


Fig. 3 Effects of irrigation levels, planting patterns, and weed control on cowpea and buckwheat grain yield. Irrigation levels include 100% (full irrigation), 85% (deficit irrigation), and 70% (severe deficit irrigation). Planting patterns consist of 100 C (cowpea monoculture), 100B (buckwheat monoculture), 25B–75 C (1 buckwheat row+3 cowpea

rows), 50B–50 C (1 buckwheat row+1 cowpea row), and 75B–25 C (3 buckwheat rows+1 cowpea row). Weed control treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing. Boxes with bars represent the mean and variations

delayed weeding were highest in sole crops: buckwheat lost 45% under full irrigation and 35% under 70% irrigation, while cowpea losses reached 51% and 31%, respectively. The 50B–50 C intercropping pattern mitigated yield losses, demonstrating its advantage under water-limited conditions.

Biomass

Buckwheat and cowpea biomass responded similarly to grain yield patterns (Fig. 4). Buckwheat monoculture achieved the highest biomass under full irrigation (5894 kg ha⁻¹ for six-week weed control), with minimal differences compared to eight-week treatments. Cowpea monoculture peaked at 3139 kg ha⁻¹ under eight-week weed control. At 85% and 70% irrigation, biomass trends were consistent, with minor differences between six- and eight-week weed-control periods.

Intercropping consistently reduced biomass relative to monocultures but the 50B–50 C ratio ranked highest among intercropping treatments, reaching up to 3527 kg ha⁻¹ with eight-week weed control. Polynomial regression analysis confirmed significant effects of irrigation, planting pattern, and weed-control timing ($p < 0.05$).

Dominant Weed Species

Five species, *Amaranthus retroflexus* L., *Heliotropium europaeum* L., *Convolvulus arvensis* L., *Chenopodium album* L., and *Portulaca oleracea* L., accounted for over 60% of the

total IVI (Table 2). Weed density was significantly affected by the interaction of irrigation levels and planting patterns (Table 2, $p < 0.05$). *Amaranthus retroflexus* exhibited the highest density, particularly under full irrigation and monoculture, peaking at 10.6 plants m⁻² in cowpea monoculture, which was significantly more than any other treatment. Intercropping (50B–50 C and 75B–25 C) effectively reduced densities under full irrigation, with *A. retroflexus* declining to 4.6 and 3.3 plants m⁻², respectively. Density trends were consistent across irrigation levels, although deficit irrigation generally reduced weed populations. *Chenopodium album* displayed relatively low and stable densities across treatments. Table 2 shows the densities of the other dominant weed species under the different experimental treatments.

Weed Biomass

Weed biomass declined with increasing duration of weed control across all irrigation levels and planting patterns (Fig. 5). The steepest reduction occurred during the first four weeks of control, followed by a gradual decline. Sole cowpea plots showed the highest biomass, peaking at 123 g m⁻² under 85% irrigation with no weed control. Intercropping patterns, particularly 50B–50 C and 75B–25 C, consistently minimized weed biomass under both full and deficit irrigation. A third-order polynomial regression demonstrated strong fit ($R^2 = 0.77–0.98$), confirming consistent biomass reduction trends.

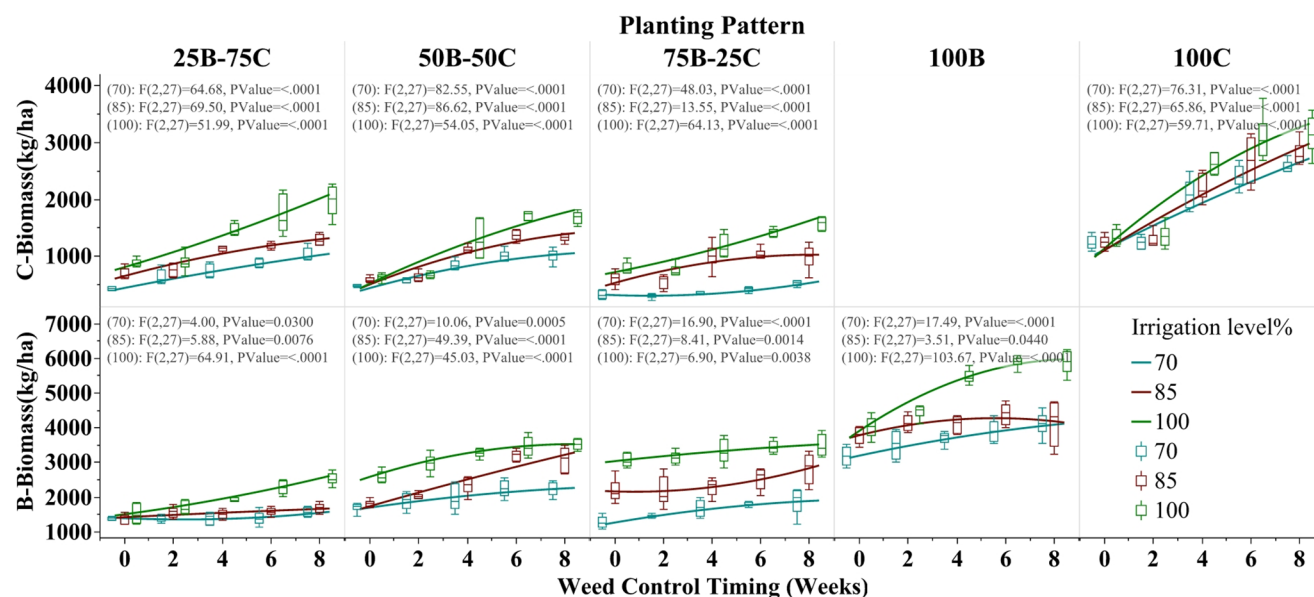


Fig. 4 Interaction of irrigation levels, planting patterns, and weed control on the biomass of cowpea and buckwheat. Irrigation levels include 100% (full irrigation), 85% (deficit irrigation), and 70% (severe deficit irrigation). Planting patterns are 100 C (cowpea monoculture), 100B (buckwheat monoculture), 25B–75 C (1 buckwheat row+3 cowpea

rows), 50B–50 C (1 buckwheat row+1 cowpea row), and 75B–25 C (3 buckwheat rows+1 cowpea row). Weed management treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing. Boxes with bars represent the mean and variations

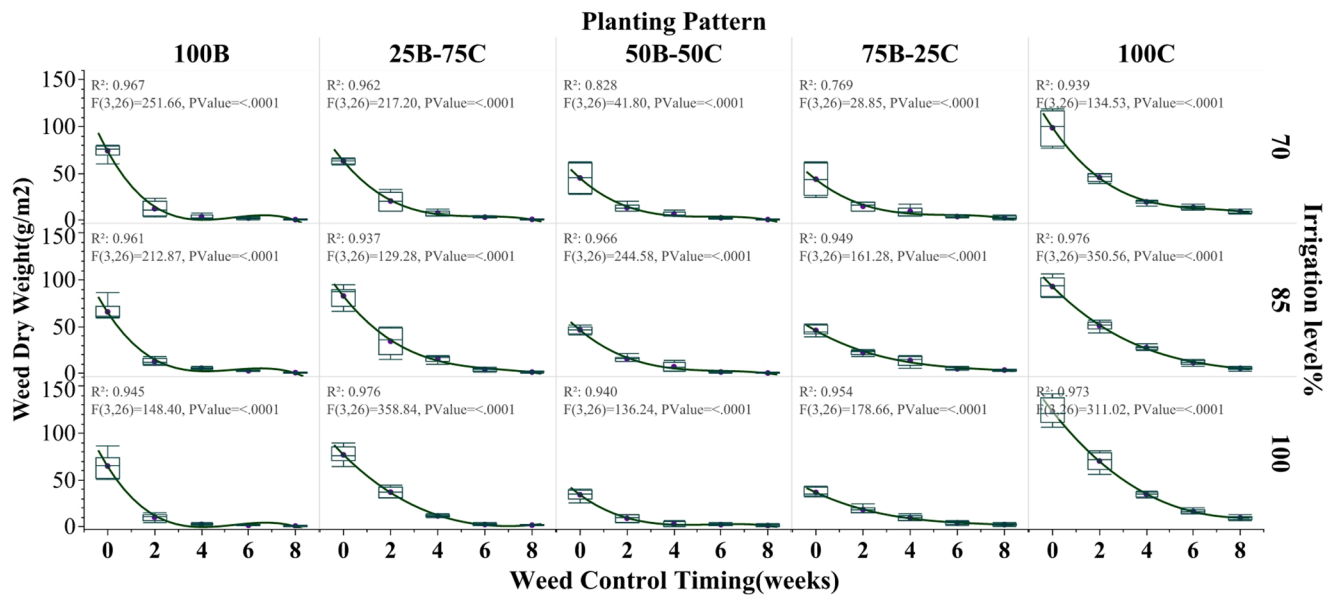


Fig. 5 Interaction of irrigation levels, planting patterns, and weed control on weed biomass. Irrigation levels include 100% (full irrigation), 85% (deficit irrigation), and 70% (severe deficit irrigation). Planting patterns are 100 C (cowpea monoculture), 100B (buckwheat monoculture), 25B-75 C (1 buckwheat row + 3 cowpea rows), 50B-50 C (1

buckwheat row + 1 cowpea row), and 75B-25 C (3 buckwheat rows + 1 cowpea row). Weed management treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing. Boxes with bars represent the mean and variations

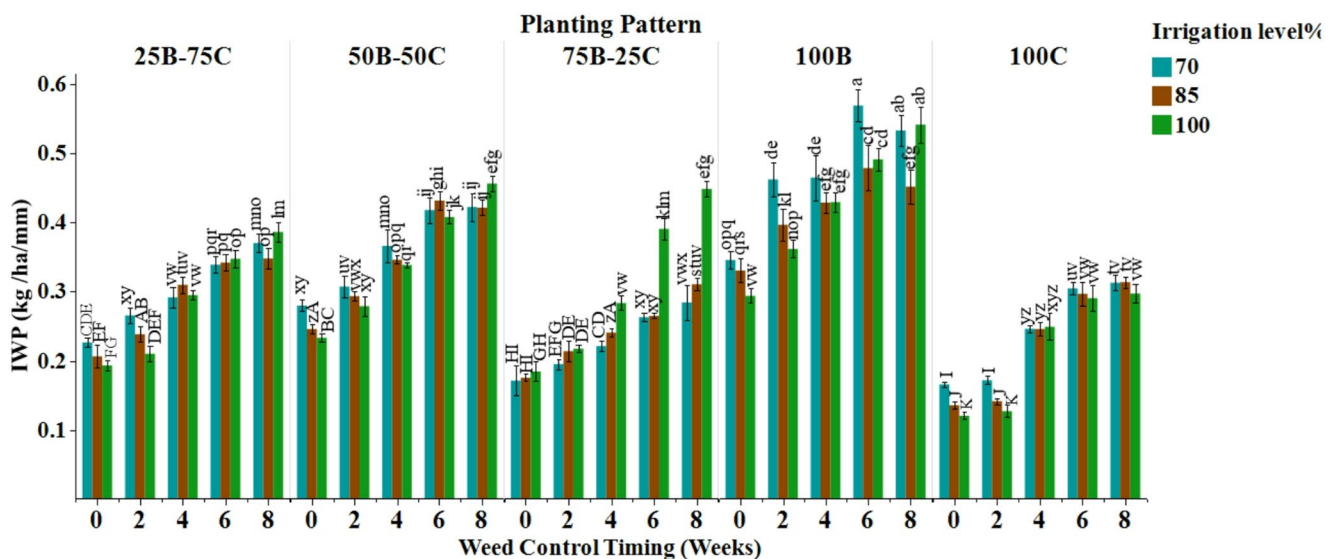


Fig. 6 Interaction of irrigation levels, planting patterns, and weed control on IWP (irrigation water productivity). Irrigation levels include 100% (full irrigation), 85% (deficit irrigation), and 70% (severe deficit irrigation). Planting patterns are 100 C (cowpea monoculture), 100B (buckwheat monoculture), 25B-75 C (1 buckwheat row + 3 cowpea rows), 50B-50 C (1 buckwheat row + 1 cowpea row), and 75B-25 C

(3 buckwheat rows + 1 cowpea row). Weed management treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing. Error bars represent the standard error of the means. Different lowercase and uppercase letters denote significant differences among treatments based on the LSD test ($P < 0.05$)

Irrigation Water Productivity (IWP)

The interaction effects of irrigation levels, planting patterns, and weed-control timing significantly affected IWP ($p < 0.05$; Fig. 6). Buckwheat monoculture achieved a maximum IWP

of $0.57 \text{ kg ha}^{-1} \text{ mm}^{-1}$ with 70% irrigation and six weeks of weed control, a value significantly higher than that of all other treatments. In contrast, cowpea monoculture recorded its lowest IWP ($0.12 \text{ kg ha}^{-1} \text{ mm}^{-1}$) under full irrigation with no weed control. Among intercropping ratios, the 50B-50 C

Table 3 ANN performance metrics for predicting vertical biomass distribution (buckwheat and cowpea)

Measures	Training	Validation	Test
R Squared	0.92	0.87	0.90
Root Mean Squared Error	0.58	0.71	0.72
Mean Absolute Error	0.32	0.4	0.41

Values of R Squared, Root Mean Squared Error, and Mean Absolute error values are reported for the training, validation, and test datasets, respectively.

pattern achieved the highest IWP ($0.46 \text{ kg ha}^{-1} \text{ mm}^{-1}$) under full irrigation with eight weeks of weed control, highlighting its superior resource use efficiency. Longer weed-control durations consistently increased IWP across all planting patterns.

Vertical Canopy Biomass

The artificial neural network (ANN) accurately predicted vertical biomass distribution (Table 3). Model performance metrics were high ($R^2 = 0.92, 0.87$, and 0.90 for training, validation, and test; $\text{RMSE} = 0.58\text{--}0.72 \text{ g m}^{-2}$; $\text{MAE} = 0.32\text{--}0.41 \text{ g m}^{-2}$).

Vertical biomass distribution was strongly influenced by planting pattern, irrigation, and weed-control duration (Figs. 7 and 8).

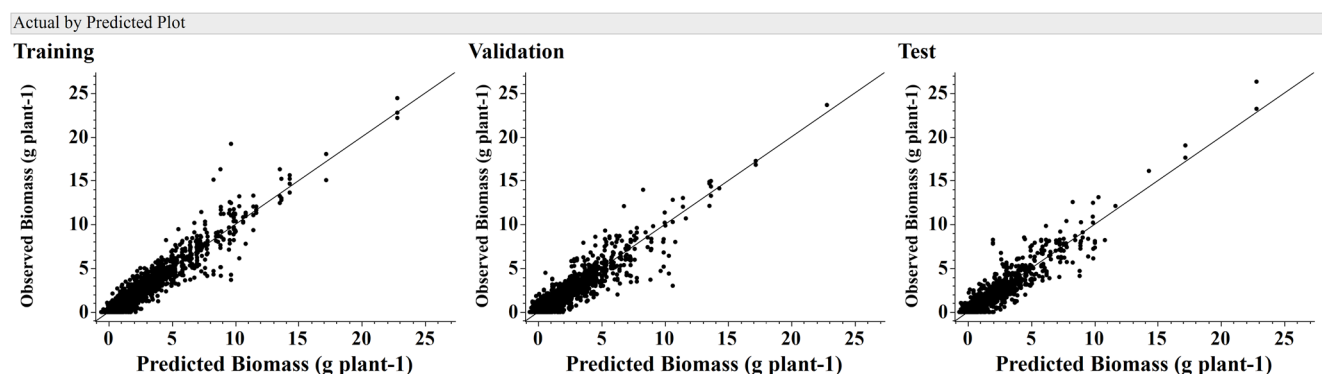
In cowpea monoculture, biomass accumulated mainly in the 20–40 cm canopy layer, reaching $\sim 3 \text{ g plant}^{-1}$ under full irrigation and eight-week weed control. In buckwheat monoculture, the 40–60 cm layer contained most biomass, peaking at 5 g plant^{-1} under full irrigation with extended weed control. Intercropping patterns (50B–50 C and 25B–75 C) concentrated biomass in the 20–60 cm canopy layers, with buckwheat producing up to 6.5 g plant^{-1} and cowpea up to 1.5 g plant^{-1} under optimal conditions. Extended weed control and full irrigation enhanced vertical biomass accumulation, while deficit irrigation and early termination of weed control reduced biomass across all canopy layers.

Land Equivalent Ratio (LER)

Figure 9 shows a significant interaction effect of irrigation levels, planting patterns, and weed-control timing on LER ($p < 0.05$). The 50B–50 C pattern consistently achieved $\text{LER} > 1.0$ across irrigation levels and weed-control durations, peaking at 1.11 under full irrigation with four weeks of weed control and under 85% irrigation with six weeks of weed control. Conversely, the 75B–25 C pattern rarely exceeded 1.0, indicating suboptimal resource use. The 25B–75 C pattern exceeded 1.0 only under early weed-control timing and higher irrigation. These results indicate that the 50B–50 C ratio maximizes intercropping efficiency, particularly under favorable water availability.

Monetary Advantage Index (MAI)

The MAI showed significant variation based on planting patterns, irrigation levels, and timing of weed control (Fig. 10). For the 50B–50 C planting pattern, MAI values were positive across all weed control timings under both 100% and 85% irrigation. The highest MAI, recorded at 655 USD ha^{-1} , occurred during an eight-week control with 100% irrigation. Under 70% irrigation without weeding, the MAI for this pattern was approximately 80 USD ha^{-1} . In contrast, the 75B–25 C planting pattern exhibited negative MAI values across all combinations of irrigation levels and weed control timings. The 25B–75 C planting pattern achieved a maximum MAI of 416 USD ha^{-1} at eight weeks under 100% irrigation, with positive values also recorded during the no-weeding and second week under both 100% and 85% irrigation (Fig. 10).

**Fig. 7** Scatter plots of predicted versus observed vertical biomass distribution (g m^{-2}) for the ANN model: Training, Validation and Test datasets

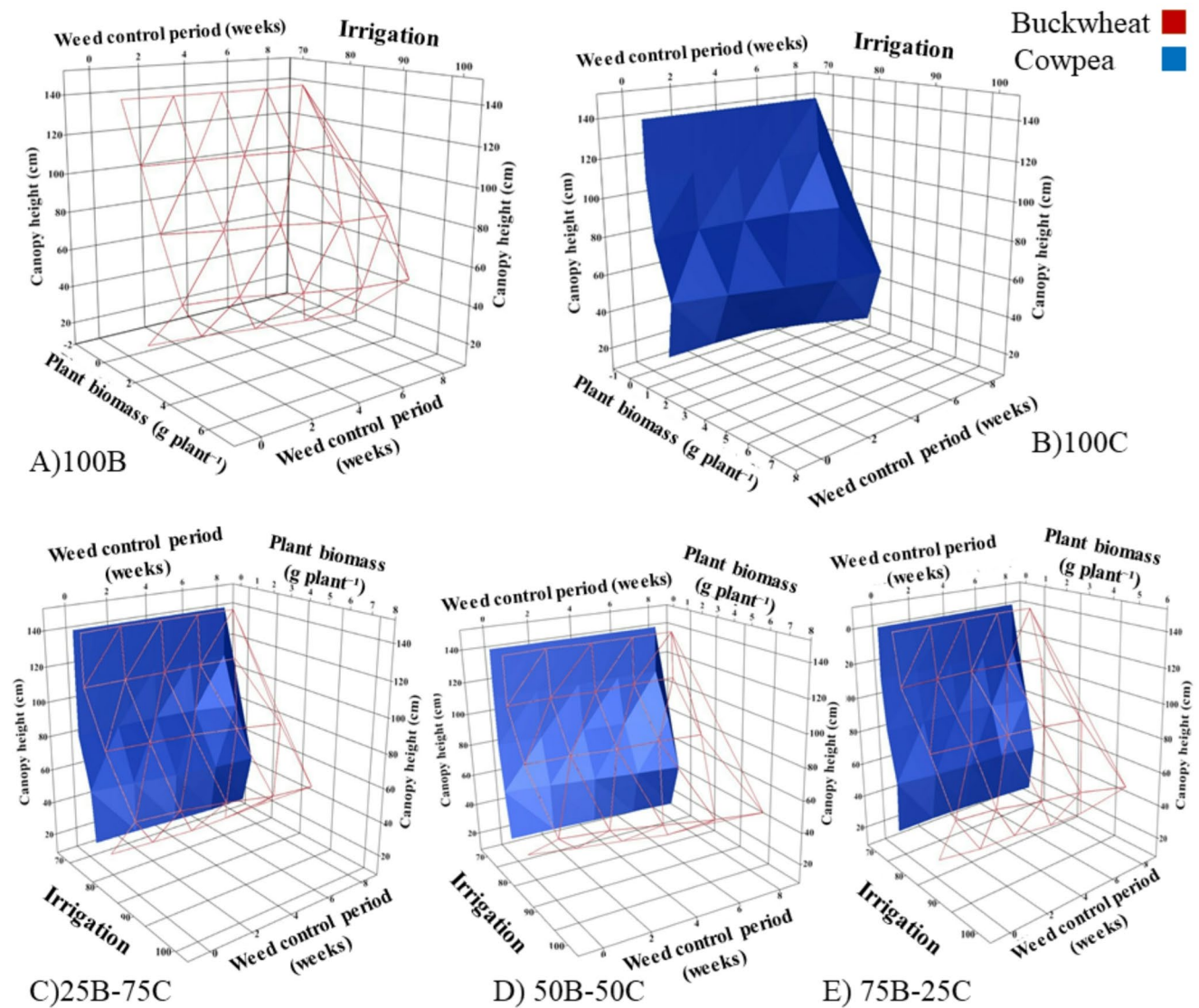


Fig. 8 Interaction effects of irrigation level, planting pattern and weed control period on the vertical distribution of biomass in buckwheat and cowpea across canopy height. Irrigation levels include 100% (full irrigation), 85% (deficit irrigation), and 70% (severe deficit irrigation). Planting patterns are 100 C (cowpea monoculture), 100B (buckwheat

monoculture), 25B-75 C (1 buckwheat row+3 cowpea rows), 50B-50 C (1 buckwheat row+1 cowpea row), and 75B-25 C (3 buckwheat rows+1 cowpea row). Weed management treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing

Discussion

Optimizing Yield and Biomass in Buckwheat–Cowpea Intercropping

The superior performance of intercropped systems, particularly the 50B–50 C arrangement, underscores the ecological advantage of balanced species proportions in enhancing complementarity and resource-use efficiency. The consistent LER values above unity indicate that interspecific facilitation outweighed competitive effects, likely due to improved spatial and temporal niche differentiation between buckwheat and cowpea (Gu et al., 2021; Lebreton et al., 2024).

Interspecific interactions appear to promote more efficient canopy stratification and soil resource partitioning, allowing both species to exploit available light and moisture more effectively under variable water supply (Yin et al., 2020).

The enhanced performance of buckwheat in mixed stands suggests that reduced intraspecific competition, coupled with the contrasting architecture of cowpea, improved light interception and photosynthetic efficiency in lower canopy layers. Morphological adjustments, such as shorter stature and compact canopy in intercropped buckwheat, likely minimized self-shading while optimizing vertical resource capture. These adaptive structural responses align with reports by Byszczak et al. (2020) and Koffi et al. (2025), who found

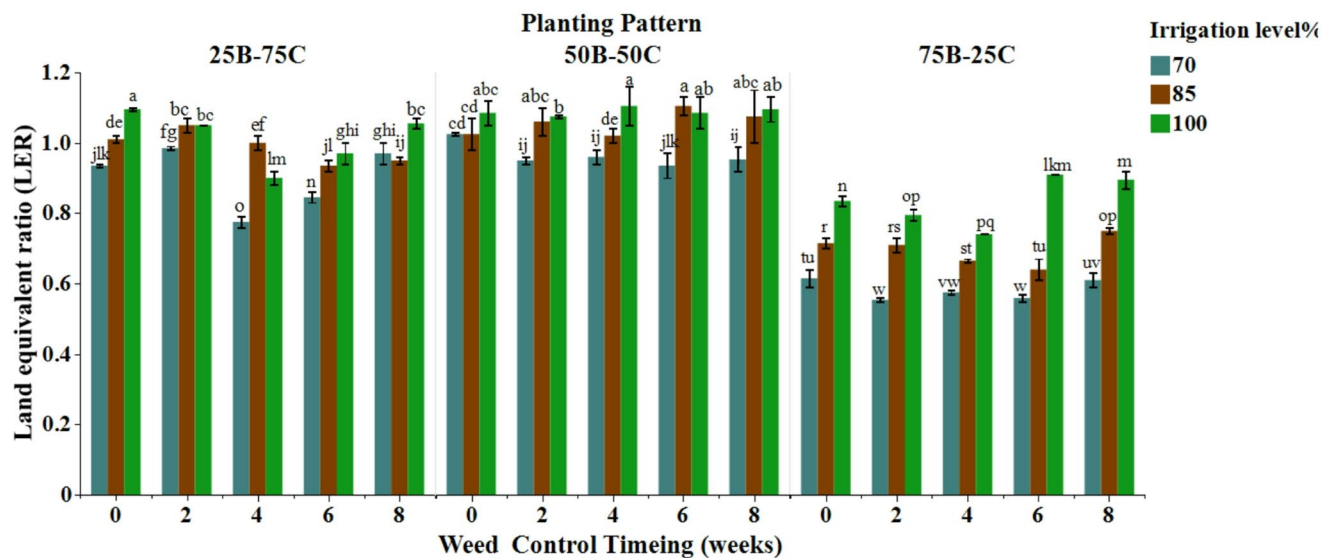


Fig. 9 Interaction of irrigation levels, planting patterns, and weed control on Land Equivalent Ratio (LER). Irrigation levels include 100% (full irrigation), 85% (deficit irrigation 85%), and 70% (deficit irrigation 70%). Planting patterns are 25B-75 C (1 buckwheat row+3 cowpea rows), 50B-50 C (1 buckwheat row+1 cowpea row), and

75B-25 C (3 buckwheat rows+1 cowpea row). Weed management treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing. Error bars represent the standard error of the means. Different lowercase letters denote significant differences among treatments based on the LSD test ($P < 0.05$)

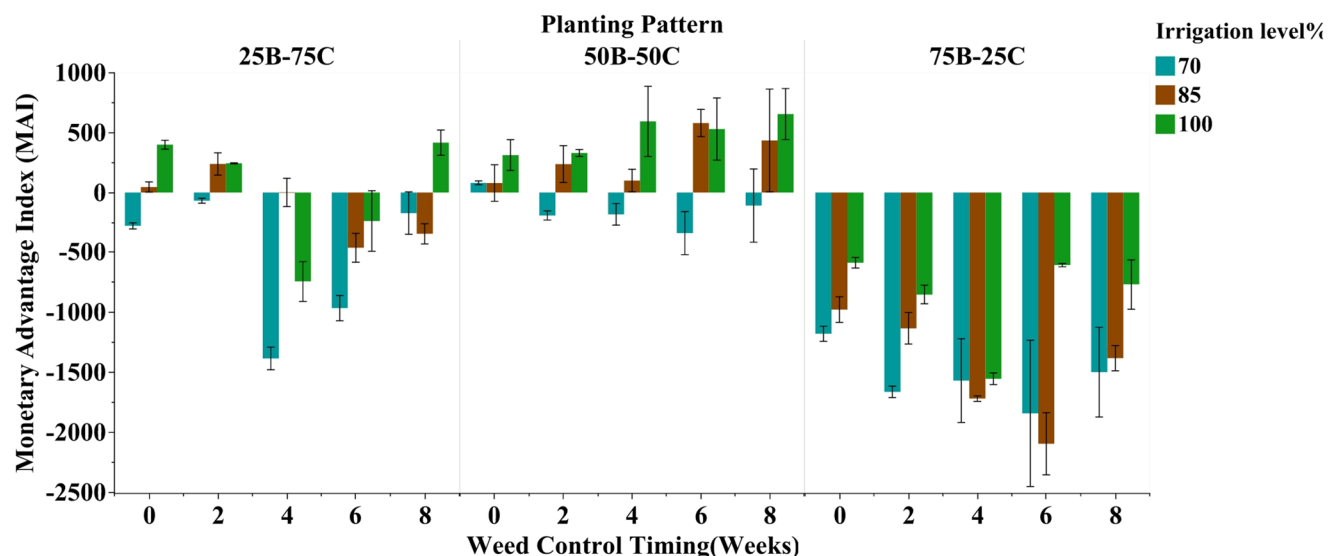


Fig. 10 Interaction of irrigation levels, planting patterns, and weed control on Monetary Advantage Index (MAI). Irrigation levels include 100% (full irrigation), 85% (deficit irrigation 85%), and 70% (deficit irrigation 70%). Planting patterns are 25B-75 C (1 buckwheat row+3 cowpea rows), 50B-50 C (1 buckwheat row+1 cowpea row), and 75B-

25 C (3 buckwheat rows+1 cowpea row). Weed management treatments include no weeding (0) and weeding until the 2nd, 4th, 6th, or 8th week after sowing. Error bars represent the standard error of the means

that alternating cereal–legume rows increase resource complementarity and overall productivity. Similarly, Li et al. (2025) and Wu et al. (2025) demonstrated that intercropping enhances dry matter allocation and yield stability through improved vertical biomass distribution and reduced height plasticity.

Under deficit irrigation, the buffering effect of intercropping further illustrates the resilience of mixed stands to water limitation. By distributing biomass across canopy layers and suppressing weed growth, intercropping likely reduced competition for water and nutrients while sustaining photosynthetic activity. These synergistic effects highlight the potential of buckwheat–cowpea intercropping as

a viable strategy for maintaining stable yields and efficient resource use in semi-arid cropping systems increasingly exposed to drought stress.

Influence of Treatments on Irrigation Water Productivity (IWP)

Buckwheat monoculture consistently recorded the highest IWP, followed by the 50B–50 C intercropping pattern, whereas cowpea monoculture exhibited the lowest values. Buckwheat's superior IWP is attributed to its rapid early growth, efficient soil coverage, and greater water extraction capacity, which minimize evaporative losses (Martínez-Goñi et al., 2023; Tursun et al., 2018; Worthing et al., 2025). In intercropping systems, differences in rooting depth and canopy architecture reduce direct competition for water, enabling more balanced soil moisture utilization (Guo et al., 2024).

The 50B–50 C arrangement achieved high IWP due to its smaller, complementary canopy, which lowered evaporative demand while maintaining productivity. Effective weed management further enhanced IWP by reducing competition for water. These findings are consistent with previous research (Demie et al., 2025; Li et al., 2025; Liu et al., 2025) demonstrating that intercropping optimizes water use through rapid growth, smaller canopy size, and reduced soil evaporation. Smaller canopies and water-conserving crop architecture, as noted by Blum (2009) and Farooq et al. (2019), further enhance IWP under water-limited conditions. Thus, the 50B–50 C intercropping pattern offers a practical strategy for improving irrigation efficiency and resilience in semi-arid environments.

Weed Suppression in Intercropping

Intercropping buckwheat and cowpea substantially reduced weed density and biomass compared to monocultures, demonstrating its effectiveness as a weed management strategy. The dense canopy formed by complementary growth habits limited light and space for weed establishment (Bastiaans & van der Werf, 2025; Sreekanta et al., 2024). Buckwheat's rapid early biomass accumulation was key, while cowpea contributed additional shading and ground coverage. Even under water stress, intercropping suppressed weeds effectively by occupying vertical space that weeds would otherwise exploit (Fig. 7). In contrast, cowpea monoculture was less effective at suppressing weeds because of its slow early growth and weaker competitiveness during the initial stages, consistent with previous findings (Baraibar et al., 2018; Dennis et al., 2024). These observations are consistent with prior studies (Cheriere et al., 2023; Lami et al., 2024), which highlighted early canopy development as critical for weed

suppression. Potential allelopathic effects of buckwheat may also contribute to reduced weed density (Sturm et al., 2018; Vieites-Álvarez et al., 2024). Stomph et al. (2020) and Oveisi et al. (2021) similarly reported that intercropping outperforms monoculture in limiting weed growth. Collectively, our results confirm that buckwheat–cowpea intercropping provides a sustainable approach to weed management, particularly under water-limited conditions.

Land Equivalent Ratio as a Measure of Intercropping Efficiency

Intercropping buckwheat and cowpea improved LER relative to monocultures, with the 50B–50 C ratio consistently exceeding 1.0. The gains in LER are attributed to reduced interspecies competition, complementary use of resources, and vertical canopy stratification, which simultaneously improve crop productivity and suppress weeds. In the 50B–50 C planting ratio, cowpea exhibited low competition with buckwheat for resources, enabling effective canopy stratification that enhanced weed suppression, resource use efficiency, and LER (Gu et al., 2021; Bastiaans & van der Werf, 2025; Carey & Nair, 2025).

Monocultures often experience high intraspecific competition, producing taller plants with lower biomass and yield (Chen et al., 2020). Intercropping maintains balanced canopy structure, ensuring stable LER under both optimal and stress conditions. These results corroborate previous findings, which suggest that interspecies complementarity enhances system stability and resource-use efficiency (Yin et al., 2020; Demie et al., 2025).

The 75B–25 C pattern displayed lower LER, consistent with observations that high competition reduces land-use efficiency (Namatsheve et al., 2020). The results indicate that a balanced intercropping ratio of 50B–50 C, along with full or moderate irrigation and timely weed control, achieves the highest LER and maximizes economic profitability due to optimized yields and market value. In contrast, the 75B–25 C planting pattern yields less buckwheat. Although buckwheat has a higher market value than cowpea, this pattern ultimately leads to reduced overall economic profitability (Rotili et al., 2023). Overall, our findings demonstrate that well-structured buckwheat–cowpea intercrops optimize land and water use, particularly in weed-competitive and water-limited environments (Figs. 11).

Conclusion

Intercropping buckwheat and cowpea in a 50–50 ratio significantly improved irrigation water productivity, consistently achieving land equivalent ratios above one and reducing

Evaluation of Resource Use Efficiency in Buckwheat–Cowpea Intercropping under Semi-arid Conditions

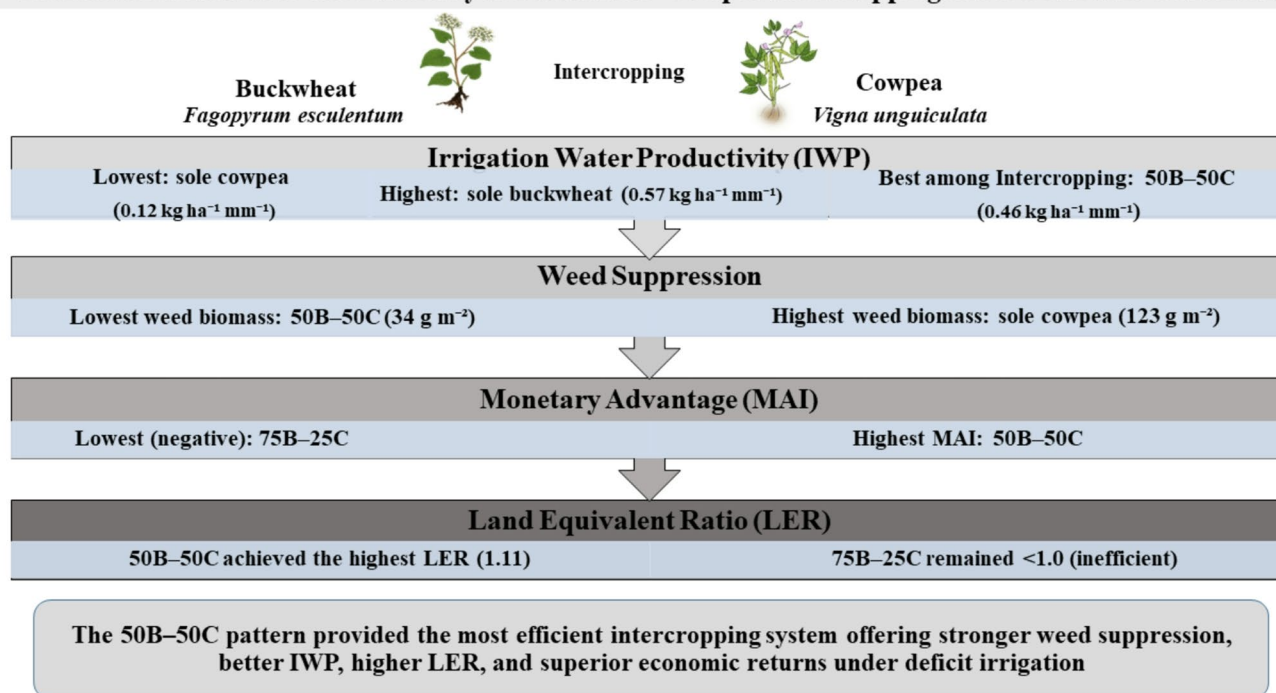


Fig. 11 Overview of the study's key findings, demonstrating the advantages of intercropping in weed suppression, IWP, and LER

the time required for effective weed control. The dynamic canopy structure emerged as a crucial factor in both weed suppression and water conservation, facilitating efficient crop interactions and resource capture. These findings position intercropping not merely as a cropping choice but as a resilient strategy for sustainable production in water-limited conditions. Future research into belowground interactions is expected to uncover the hidden mechanisms driving these positive feedbacks, further enhancing the potential for high-efficiency, climate-smart intercropping systems.

Author Contributions Kiavash Arvin performed and managed field experiments, data curation, data analysis, preparing the draft, and editing. Muhammad Bagher Hosseini was responsible for conceptualization and preparing resources. Farzaneh Zamani contributed to data curation and preparing the draft. Fariroo Abbasilakhani and Shamisa Teymoori were involved in data curation and preparing the draft. Péter Pocza contributed to data analysis, editing, and manuscript revision. Mostafa Oveisi was responsible for conceptualization, methodology, data analysis, as well as review and editing.

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Data Availability The data set used and/or analysed in the current study are available from the corresponding authors upon reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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