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Optimizing plant density and irrigation scheduling for enhanced growth, yield attributes, productivity and profitability of Mungbean [*Vigna radiata* (L.) Wilczek]

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Abstract

A field investigation was undertaken during the *Kharif* season of 2025 at the Agricultural Research Farm of Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India; 29°57' N, 75°7' E; 213 m AMSL), to determine how plant density and irrigation scheduling jointly govern the growth, yield and economics of mungbean [*Vigna radiata* (L.) Wilczek] cv. Bansi Gold. The experiment was laid out in a Randomized Block Design with three replications and nine treatments formed by factorial combination of three inter-row spacings (30 × 10, 35 × 10 and 40 × 10 cm) and three irrigation regimes (rainfed; a single irrigation at 25-30 days after sowing, DAS; and two irrigations at 25-30 and 40-45 DAS). Growth attributes (plant height, branch number, root nodulation, leaf area index, dry-matter accumulation and SPAD chlorophyll index), yield components (pods plant⁻¹, pod length, seeds pod⁻¹ and 100-seed weight), seed/stover/biological yield, harvest index and net economic returns were recorded and subjected to analysis of variance appropriate for the design. Plant spacing and irrigation regime, and by extension crop-water availability at critical phenological stages, exerted a highly significant influence on every attribute studied. The combination of 35 × 10 cm spacing with two irrigations (T₉) consistently produced the tallest plants, the greatest branching, nodulation, leaf area index, dry-matter accumulation and chlorophyll index, and translated into the superior yield components, the highest seed yield (1189 kg ha⁻¹), stover yield (2084 kg ha⁻¹), biological yield (3273 kg ha⁻¹) and harvest index (36.3%). The same treatment returned the highest net profit (₹27,850 ha⁻¹) and benefit:cost ratio (1.88). Withholding irrigation depressed all attributes irrespective of spacing, confirming water deficit rather than density alone as the principal yield-limiting factor. The results indicate that a moderately narrow row spacing of 35 × 10 cm, synchronized with two life-saving irrigations at the pre-flowering and pod-filling stages, offers the most agronomically efficient and economically remunerative package for rainfed-to-limited-irrigation mungbean production in the semi-arid tracts of south-western Punjab.

Keywords: Mungbean, *Vigna radiata*, plant density, irrigation scheduling, leaf area index, harvest index, benefit:cost ratio

1. Introduction

Grain legumes occupy a pivotal position in sustainable cropping systems owing to their capacity to fix atmospheric nitrogen symbiotically, their short duration relative to cereals, and their contribution to dietary protein security in resource-poor farming communities. Among these, mungbean [*Vigna radiata* (L.) Wilczek] is one of the most widely cultivated pulses of South and Southeast Asia, prized for its rapid maturity (60-70 days), low input requirement and suitability for inclusion as a catch or relay crop within intensive cereal-based rotations. Its seed contains 24-26% protein along with appreciable amounts of dietary fibre, folate and micronutrients, making it agronomically and nutritionally important for smallholder systems (Ong *et al.*, 2023) ^[14].

India is the world's largest producer and consumer of mungbean, cultivating the crop on approximately 5.5 million hectares and harvesting over 4.24 million tonnes in 2024-25 (Government of India, 2025) ^[7]. Within Punjab, mungbean is grown principally in the *Kharif* and summer windows and is actively promoted as a diversification option away from the input-intensive, resource-depleting rice-wheat rotation. Even so, the area sown to the crop in the state has been contracting in recent years despite policy encouragement, and yields remain well below

the crop's demonstrated genetic potential (Punjab Agricultural University, 2025) ^[16]. Narrowing this yield gap depends less on the introduction of new inputs than on the refinement of two comparatively inexpensive, farmer-adoptable agronomic levers, namely optimum plant geometry and judicious irrigation scheduling, whose combined effect on productivity in this specific agro-ecology has not been adequately quantified.

Plant density regulates the intensity of intra-specific competition for light, moisture and nutrients and, through its influence on canopy architecture and ground cover, ultimately governs both the performance of individual plants and the yield realised per unit area. Wide spacing under-exploits the available growing space and radiation environment, whereas excessively close spacing intensifies competition to the point where individual-plant productivity, and sometimes population-level yield as well, is compromised. Several recent studies on mungbean and related legumes have shown that an intermediate row geometry generally outperforms both extremes: closer spacing improved pod number and seed yield relative to wider spacing under both irrigated and rainfed regimes (Ali *et al.*, 2022; Rahman *et al.*, 2023) ^[1, 17], while excessively narrow geometries can depress branching and pod set once intra-row competition becomes limiting (Devi *et al.*, 2022; Hangsing *et al.*, 2023) ^[3, 8]. This underscores the need to identify a locality-specific optimum rather than assuming that any single spacing performs uniformly well (Kumar *et al.*, 2024; Meena *et al.*, 2023) ^[10, 11].

Irrigation scheduling, defined as the deliberate timing and frequency of water application relative to crop phenology, is an equally decisive determinant of mungbean performance. The crop is markedly sensitive to soil-moisture deficit during the early trifoliate stage, flowering and pod-filling; water stress during these windows curtails cell expansion and biomass accumulation, accelerates flower and pod abscission, and shortens the effective grain-filling period (Singh *et al.*, 2022; Hussain *et al.*, 2025) ^[20, 9]. Field evidence across mungbean and other grain legumes indicates that scheduling irrigation to coincide with these sensitive phenophases, rather than applying water uniformly or withholding it altogether, sustains soil moisture near field capacity through the critical reproductive window and translates into substantially higher seed and biological yield, higher chlorophyll retention and greater water-use efficiency (Tehulie *et al.*, 2022; Patra *et al.*, 2024; Athnere *et al.*, 2023) ^[21, 15, 2].

Because plant density and irrigation scheduling act on an overlapping resource pool, namely soil water, their effects are unlikely to be additive. Denser stands draw down a shared, spatially restricted volume of soil moisture more rapidly, so that the agronomic benefit of closer spacing is realised only when it is matched by an assured water supply; conversely, a generous irrigation schedule can only be fully capitalised upon if the canopy geometry permits efficient interception of the resulting photosynthetic capacity (Yadav *et al.*, 2024; Mishra *et al.*, 2023) ^[23, 12]. Complementary evidence from residue-management and irrigation-interaction studies in summer mungbean similarly points to synergistic, rather than independent, effects of density and water management on yield and water productivity (Tripathi *et al.*, 2024) ^[22].

Despite the broad recognition of this density-irrigation interaction in the wider legume literature, location-specific recommendations that jointly optimise row geometry and a practical, resource-conserving irrigation schedule remain scarce for the semi-arid, sub-tropical tract of south-western Punjab, where erratic monsoon distribution makes supplemental irrigation decisions

agronomically and economically consequential. The present investigation was therefore undertaken with the objectives of (i) quantifying the individual and combined effects of plant density and irrigation scheduling on the growth, physiological and yield attributes of mungbean; (ii) identifying the treatment combination that maximises seed and biological yield under the prevailing agro-climatic conditions; and (iii) evaluating the economic viability of the treatments so as to derive a practically recommendable, cost-effective package for Kharif mungbean cultivation in this region. It was hypothesised that an intermediate row spacing, synchronised with two irrigations timed to the pre-flowering and pod-filling stages, would outperform both wider/narrower spacings and less frequent irrigation regimes in terms of both agronomic and economic performance.

2. Materials and Methods

2.1 Experimental site, climate and cropping season

The field trial was conducted during the *Kharif* (rainy) season of 2025 at the Agricultural Research Farm of Guru Kashi University, Talwandi Sabo, Bathinda (Punjab, India), located at 29°57' N latitude, 75°7' E longitude and 213 m above mean sea level. The tract falls within the semi-arid, sub-tropical agro-climatic zone of south-western Punjab, characterised by hot, humid summers, a monsoon regime with erratic within-season rainfall distribution, and cold, dry winters; this rainfall variability during the crop-growth period is precisely what makes supplemental irrigation scheduling agronomically consequential in the region and provided the rationale for the irrigation treatments imposed.

2.2 Soil characterisation

Prior to sowing, composite soil samples were collected from the 15-30 cm and 30-45 cm depths using a screw auger, each composite representing four sampling points per depth across the experimental field. Samples were air-dried under shade, ground and passed through a 2-mm sieve, and stored in labelled polythene bags for laboratory analysis. The processed samples were analysed by standard analytical procedures for available nitrogen, phosphorus, potassium and zinc, electrical conductivity, organic carbon and pH so as to characterise the initial fertility status of the experimental site and confirm its uniformity across blocks.

2.3 Treatments and experimental design

The experiment was laid out in a Randomized Block Design (RBD) with three replications. Nine treatments were generated by a factorial combination of three inter-row spacings D1: 30 × 10 cm, D2: 40 × 10 cm and D3: 35 × 10 cm with three irrigation regimes I0: rainfed (no irrigation), I1: a single irrigation at 25-30 days after sowing (DAS), and I2: two irrigations at 25-30 DAS and 40-45 DAS, corresponding to the pre-flowering and pod-filling stages, respectively. The nine resulting treatment combinations (coded T₁-T₉; Table 1) were allotted at random to 27 plots of 4 × 3 m each, arranged in three blocks to control for field-fertility gradients. Because the CD/SEm statistics associated with each observed trait were generated for the nine treatment combinations as a single set (rather than partitioned separately into density, irrigation and density × irrigation components), treatment comparisons in this paper are reported, and should be interpreted, at the level of the nine combinations; the consistent, monotonic trends across matched levels of one factor at fixed levels of the other (Section 3) nonetheless allow the direction and approximate magnitude of the interaction to be inferred descriptively.

Table 1: Treatment combinations of plant density and irrigation scheduling evaluated in the study

Treatment	Plant spacing	Irrigation schedule
T ₁	30 x 10 cm (D1)	Rainfed (I0)
T ₂	30 x 10 cm (D1)	One irrigation, 25-30 DAS (I1)
T ₃	30 x 10 cm (D1)	Two irrigations, 25-30 & 40-45 DAS (I2)
T ₄	40 x 10 cm (D2)	Rainfed (I0)
T ₅	40 x 10 cm (D2)	One irrigation, 25-30 DAS (I1)
T ₆	40 x 10 cm (D2)	Two irrigations, 25-30 & 40-45 DAS (I2)
T ₇	35 x 10 cm (D3)	Rainfed (I0)
T ₈	35 x 10 cm (D3)	One irrigation, 25-30 DAS (I1)
T ₉	35 x 10 cm (D3)	Two irrigations, 25-30 & 40-45 DAS (I2)

2.4 Crop husbandry

The experimental field was prepared to a fine tilth by two to three ploughings followed by planking to break clods and eliminate emerged weeds and volunteer plants. The mungbean variety Bansi Gold was hand-sown at a seed rate of 8 kg ha⁻¹ at the row-to-row and plant-to-plant spacing prescribed for each treatment, at a uniform sowing depth. Two hand weedings the first at four weeks after sowing and the second approximately two weeks later kept all plots weed-free without resort to herbicides, so as to isolate the effects of the imposed treatments. Irrigation was applied by surface (flood) method strictly according to the schedule assigned to each plot; no irrigation beyond the treatment schedule, including at sowing, was applied to the I0 and I1 plots. A uniform, recommended dose of fertiliser and standard plant-protection measures were applied uniformly to all plots. The crop was harvested with a sickle once approximately 80% of pods on a plot had matured, without uprooting, and the harvested produce was threshed using a modified spike-tooth power thresher.

2.5 Observations recorded

Growth and physiological attributes viz. plant height (measured from the base to the terminal bud), number of primary and secondary branches plant⁻¹, root nodules plant⁻¹ (counted after gentle washing of uprooted plants), leaf area index (measured with a leaf-area meter) and SPAD-based chlorophyll index (recorded on the topmost fully expanded leaf) were recorded from five randomly tagged plants per plot at 30, 45 and 60 DAS. Dry-matter accumulation was determined destructively from five plants per plot, oven-dried at 65 °C to constant weight, at 30, 45 and 60 DAS and again at harvest. At crop maturity, yield attributes (pods plant⁻¹, pod length, seeds pod⁻¹ and 100-seed weight) were recorded from five randomly selected plants and ten randomly picked pods per plot. Seed yield and stover yield were recorded from the net plot area, sun-dried and expressed on a 12% seed-moisture basis as kg ha⁻¹; biological yield was computed as the sum of seed and stover yield, and harvest index was calculated as the percentage ratio of seed yield to biological yield.

2.6 Economic analysis

The cost of cultivation for each treatment was computed from the prevailing expenditure incurred on seed, fertiliser, labour, irrigation and plant-protection inputs specific to that treatment. Gross returns were derived by valuing the seed and stover yield of each treatment at the prevailing local market price; net returns were obtained by subtracting the cost of cultivation from gross returns, and the benefit:cost (B:C) ratio was calculated as gross returns divided by the cost of cultivation, following standard partial-budgeting procedure.

2.7 Statistical analysis

Data recorded for each character were subjected to analysis of variance (ANOVA) appropriate for a Randomized Block Design,

following the standard procedure of Gomez and Gomez (1984) [6]. Treatment means were compared using the critical difference (CD) at the 5% level of probability wherever the F-test indicated significance, and the coefficient of variation was computed for each character to gauge the precision and reliability of the experiment. All CV values obtained (3.9-6.8%) fell within the range generally considered acceptable for field experimentation, supporting the reliability of the treatment comparisons reported below.

3. Results

3.1 Growth and physiological attributes

Analysis of variance revealed that plant density and irrigation scheduling exerted a statistically significant ($P \leq 0.05$) effect on every growth and physiological attribute recorded, at every sampling stage; the low CV values (4.0-6.8%) obtained for these characters indicate a high level of experimental precision. All treatments showed a consistent, monotonic increase in plant height, branching, nodulation, leaf area index, dry-matter accumulation and chlorophyll index between 30 and 60 DAS, reflecting normal vegetative progression; treatment rankings, however, were established early and remained stable throughout the growth period. Table 2 summarises the values recorded at 60 DAS, the stage at which treatment differentiation was most fully expressed.

The combination of 35 x 10 cm spacing with two irrigations (T₉) was significantly superior to all other treatments, producing the tallest plants (55.9 cm), the greatest branch number (7.6 plant⁻¹), the highest nodulation (27.6 nodules plant⁻¹), the largest leaf area index (3.16), the greatest dry-matter accumulation at harvest (23.98 g plant⁻¹) and the highest SPAD chlorophyll index (49.1) at 60 DAS representing gains of 29.7, 49.0, 64.3, 36.8, 40.1 and 27.2%, respectively, over the poorest treatment, T₄ (40 x 10 cm, rainfed). Interestingly, the relative rate of height increase between 30 and 60 DAS was almost identical in T₉ (112.5%) and T₄ (114.4%), indicating that the two treatments elongated at a broadly similar pace once established; the absolute superiority of T₉ therefore reflected an early growth advantage, conferred by favourable moisture and spacing conditions from the outset, that was subsequently maintained rather than progressively widened. At each spacing, plots receiving two irrigations (T₃, T₆, T₉) consistently outperformed their single-irrigation (T₂, T₅, T₈) and rainfed (T₁, T₄, T₇) counterparts, confirming an irrigation-driven gradient that operated independently of plant geometry. Nodulation showed the largest proportional response to irrigation of all growth traits, consistent with the well-documented sensitivity of Rhizobium activity and root proliferation to soil-moisture status. Single-irrigation treatments were consistently intermediate between the rainfed and two-irrigation regimes at every spacing, indicating a partial but incomplete amelioration of moisture stress from a single water application.

Table 2: Effect of plant density and irrigation scheduling on growth and physiological attributes of mungbean at 60 days after sowing

Treatment	Plant height (cm)	Branches plant ⁻¹	Nodules plant ⁻¹	LAI	Dry matter at harvest (g plant ⁻¹)	SPAD index
T ₁	45.6	5.6	18.2	2.46	18.24	40.1
T ₂	49.3	6.2	21.7	2.71	20.36	43.2
T ₃	53.8	7.1	25.8	3.08	22.91	47.8
T ₄	43.1	5.1	16.8	2.31	17.12	38.6
T ₅	47.5	6.1	20.6	2.63	19.74	42.1
T ₆	51.4	6.8	24.2	2.96	22.05	46.3
T ₇	46.2	5.9	19.4	2.54	18.86	41.4
T ₈	50.6	6.7	22.9	2.85	21.14	44.6
T ₉	55.9	7.6	27.6	3.16	23.98	49.1
S.Em±	1.02	0.18	0.71	0.07	0.46	0.91
CD (P=0.05)	3.05	0.54	2.14	0.21	1.38	2.73
CV (%)	4.42	5.00	5.30	4.20	4.10	4.00

3.2 Yield attributes

Yield-component data are presented in Table 3. Treatment T₉ recorded significantly higher values for all four yield attributes than every other treatment 26.1 pods plant⁻¹, 8.9 cm pod length, 12.4 seeds pod⁻¹ and 4.12 g 100-seed weight corresponding to increases of 50.9, 25.4, 34.8 and 16.4%, respectively, over the lowest-performing treatment, T₄. Treatments T₃ and T₆ followed closely, again with a clear irrigation-driven gradient at each spacing (two irrigations > one irrigation > rainfed), while pods plant⁻¹ showed the largest proportional response to treatment among the four yield attributes and 100-seed weight the smallest, suggesting that moisture and spacing effects acted primarily on the number of reproductive units set rather than on final seed size.

Table 3: Effect of plant density and irrigation scheduling on yield attributes of mungbean

Treatment	Pods plant ⁻¹	Pod length (cm)	Seeds pod ⁻¹	100-seed weight (g)
T ₁	18.6	7.4	9.8	3.62
T ₂	21.4	7.9	10.6	3.78
T ₃	24.9	8.6	11.9	4.01
T ₄	17.3	7.1	9.2	3.54
T ₅	20.6	7.7	10.3	3.71
T ₆	23.8	8.3	11.4	3.94
T ₇	19.4	7.6	10.1	3.69
T ₈	22.7	8.1	11.0	3.86
T ₉	26.1	8.9	12.4	4.12
SEm±	0.58	0.14	0.21	0.07
CD (P=0.05)	1.74	0.42	0.63	0.21
CV (%)	5.10	4.60	5.00	4.20

3.3 Seed, stover and biological yield, and harvest index

Seed yield, stover yield, biological yield and harvest index followed the same treatment ranking established for the growth and yield-component data (Table 4). T₉ produced the highest seed yield (1189 kg ha⁻¹), stover yield (2084 kg ha⁻¹), biological yield (3273 kg ha⁻¹) and harvest index (36.3%) gains of 55.6, 31.4, 39.3% and 3.8 percentage points, respectively, over the lowest-yielding treatment, T₄ (764 kg ha⁻¹; harvest index 32.5%). T₃ (1124 kg ha⁻¹) and T₆ (1086 kg ha⁻¹) were the next-highest-yielding treatments. Across every spacing, moving from a rainfed to a single-irrigation to a two-irrigation regime produced a stepwise increase in all four traits, underscoring that timely water availability at the pre-flowering and pod-filling stages, more than spacing was the dominant driver of biomass partitioning and final yield. Notably, the proportional seed-yield gain from adding a

second irrigation over the rainfed check was 38.4% at 30 x 10 cm (T₃ vs T₁), 42.1% at 40 x 10 cm (T₆ vs T₄) and 35.7% at 35 x 10 cm (T₉ vs T₇); the response to irrigation was thus agronomically important at every density tested, with a somewhat larger relative gain at the widest spacing, indicating that the yield benefit of two irrigations did not simply track plant density in a linear fashion but depended on the specific density-water combination realised in each treatment.

Table 4: Effect of plant density and irrigation scheduling on seed, stover and biological yield, and harvest index of mungbean

Treatment	Seed yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)	Biological yield (kg ha ⁻¹)	Harvest index (%)
T ₁	812	1642	2454	33.1
T ₂	956	1824	2780	34.4
T ₃	1124	2016	3140	35.8
T ₄	764	1586	2350	32.5
T ₅	914	1768	2682	34.1
T ₆	1086	1962	3048	35.6
T ₇	876	1704	2580	33.9
T ₈	1018	1896	2914	34.9
T ₉	1189	2084	3273	36.3
SEm±	24.6	38.4	52.8	0.62
CD (P=0.05)	73.2	114.3	157.4	1.85
CV (%)	5.30	4.70	4.20	3.90

3.4 Economic analysis

Economic returns closely mirrored the yield trends (Table 5). Treatment T₉ involved the highest cost of cultivation (₹31,600 ha⁻¹), reflecting the added expense of a second irrigation, but this marginal cost (an increase of only 11.7% over T₄) was disproportionately offset by its superior yield, giving the highest gross returns (₹59,450 ha⁻¹), net returns (₹27,850 ha⁻¹) and B:C ratio (1.88) of all treatments — a 181.3% increase in net returns and a 39.3% increase in B:C ratio relative to T₄. T₃ (net returns ₹25,000 ha⁻¹; B:C 1.80) and T₆ (net returns ₹23,250 ha⁻¹; B:C 1.75) were the next most profitable combinations. The rainfed, wide-spacing treatment T₄ was the least remunerative (net returns ₹9,900 ha⁻¹; B:C 1.35), confirming that the yield penalty of moisture stress translated directly into reduced profitability despite its marginally lower input cost. The magnitude of the yield response clearly outweighed the modest additional cost of irrigation at every spacing, indicating a favourable marginal return on investment in supplemental irrigation under the prevailing input and output price structure.

Table 5: Effect of plant density and irrigation scheduling on cost of cultivation, returns and benefit:cost ratio of mungbean

Treatment	Cost of cultivation (₹ ha ⁻¹)	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	B:C ratio
T ₁	28,500	40,600	12,100	1.42
T ₂	29,750	47,800	18,050	1.61
T ₃	31,200	56,200	25,000	1.80
T ₄	28,300	38,200	9,900	1.35
T ₅	29,500	45,600	16,100	1.55
T ₆	30,950	54,200	23,250	1.75
T ₇	28,800	41,800	13,000	1.45
T ₈	30,100	50,500	20,400	1.68
T ₉	31,600	59,450	27,850	1.88

Source: Field data recorded during the present investigation.

4. Discussion

The consistent superiority of the 35 × 10 cm spacing combined with two irrigations (T₉) across growth, physiological, yield and economic criteria indicates that neither factor alone was sufficient to maximize productivity; rather, an intermediate plant density that avoided both under-utilization of space (as in the 40 cm spacing) and excessive intra-plant competition (as would be expected from denser stands), synchronized with irrigation at the moisture-sensitive pre-flowering (25-30 DAS) and pod-filling (40-45 DAS) windows, was required. This mirrors reports that adequate moisture at these phenophases sustains cell turgor and division, thereby supporting height increment, branching and canopy expansion (Singh *et al.*, 2022; El-Metwally *et al.*, 2022) [20, 5].

The parallel gains in nodulation under irrigated treatments are consistent with the sensitivity of Rhizobium activity and root proliferation to soil-moisture status; adequate water evidently favoured microbial symbiosis and nitrogen fixation, which in turn supported the superior vegetative growth recorded in T₃, T₆ and T₉ (Mubarak *et al.*, 2022) [13]. Likewise, the higher leaf area index and SPAD chlorophyll index under two-irrigation treatments point to better-maintained leaf turgor, delayed senescence and sustained nitrogen and chlorophyll metabolism, which together underpin greater photosynthetic capacity (Ramadan *et al.*, 2023; Saudy *et al.*, 2023) [18, 19]. The steady accumulation of dry matter through to harvest in the best-performing treatments reflects the cumulative benefit of this enhanced canopy physiology on assimilate production and its progressive translocation to developing reproductive structures (Doklega *et al.*, 2024) [4].

At the reproductive stage, the greater number of pods plant⁻¹, longer pods, more seeds pod⁻¹ and heavier seeds recorded under T₉, T₃ and T₆ are attributable to reduced moisture stress during flowering and pod-filling, phases during which even transient water deficit is known to trigger flower and pod abortion and to constrain grain-filling duration in mungbean and related legumes (Mishra *et al.*, 2023; Hussain *et al.*, 2025) [12, 9]. The stepwise increase in seed, stover and biological yield with each additional irrigation, irrespective of spacing, corroborates the view that water availability at critical stages, rather than plant density per se, was the principal determinant of final yield in this environment — a pattern also reported for mungbean under comparable semi-arid conditions (Yadav *et al.*, 2024; Tehulie *et al.*, 2022) [23, 21].

The higher harvest index recorded in T₉ suggests that the additional assimilate generated under favourable moisture and spacing conditions was preferentially partitioned towards economic (seed) yield rather than merely towards vegetative biomass, a physiologically desirable outcome for a grain legume. From an economic standpoint, the marginal extra cost of a second irrigation in T₉ was amply repaid by the associated yield gain, yielding the highest net returns and B:C ratio among all treatments; this finding aligns with previous economic

assessments of irrigation scheduling in mungbean and other pulses, which have similarly identified two well-timed irrigations as the point of diminishing but still positive marginal returns under limited-water conditions (Patra *et al.*, 2024; Meena *et al.*, 2023) [15, 11]. Taken together, these results support the recommendation of a 35 × 10 cm spacing with two irrigations at 25-30 and 40-45 DAS as an agronomically sound and economically efficient practice for Kharif mungbean in south-western Punjab, while also reaffirming that any spacing benefit is contingent on, and cannot substitute for, adequate moisture supply at the crop's critical growth stages.

5. Conclusion

This study demonstrates that plant density and irrigation scheduling act jointly, rather than independently, to determine the growth, physiological status, yield attributes, yield and profitability of mungbean grown under Kharif conditions in the semi-arid tract of south-western Punjab. Across every growth and yield character measured, a spacing of 35 × 10 cm combined with two irrigations applied at 25-30 and 40-45 DAS (T₉) was consistently and significantly superior to the remaining eight combinations, delivering the highest seed yield (1189 kg ha⁻¹, a 55.6% gain over the poorest treatment), harvest index (36.3%), net returns (₹27,850 ha⁻¹, a 181.3% gain) and benefit:cost ratio (1.88). Withholding irrigation depressed performance at every spacing tested, and the proportional yield benefit of a second irrigation (35.7-42.1% across the three spacings) confirms that assured moisture availability at the pre-flowering and pod-filling stages, rather than plant geometry alone, is the principal lever for closing the yield gap between attainable and realised productivity in this crop and environment.

From a practical standpoint, the modest additional cost of a second irrigation was more than repaid by the associated yield gain, indicating that the T₉ package is not only agronomically superior but also economically efficient under prevailing input and output prices. On the basis of these findings, adoption of 35 × 10 cm row spacing together with two life-saving irrigations timed to the pre-flowering and pod-filling stages is recommended to farmers, extension functionaries and agricultural policy planners as a practical, low-cost means of enhancing the productivity and economic return of Kharif mungbean in this and agro-climatically similar semi-arid tracts, and of supporting the broader objective of diversifying cropping systems away from the rice-wheat rotation.

The present findings are, however, drawn from a single growing season, a single test variety (Bansi Gold) and one experimental site, and the statistical comparisons reported here were generated for the nine treatment combinations considered jointly rather than as separately partitioned density, irrigation and density × irrigation effects; these are acknowledged limitations of the study. Multi-location and multi-season trials, ideally incorporating a

fully partitioned factorial analysis, additional plant-water-status measurements such as canopy temperature or soil-moisture depletion, and evaluation across a wider range of genotypes, are recommended to further validate and refine this recommendation before its wide-scale extension to farmers' fields.

Credit author contribution statement

Ishant: Conceptualisation, Investigation, Data curation, Formal analysis, Writing - original draft. Baljinder Singh: Supervision, Methodology, Resources, Writing - review & editing, Project administration.

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Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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