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Research Paper

Improving Growth, Physiological Attributes and Yield of Mungbean (*Vigna radiata L.*) Through Optimization of Irrigation Regimes in Arid Regions

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Abstract: Mungbean (*Vigna radiata* L.) growth and development are critically reduced by water deficit, necessitating optimized irrigation scheduling to achieve maximum economic yield. A field study was conducted over two consecutive growing seasons (2018 and 2019) at the Agronomic Research Station, Karor-Layyah, within an arid climatic zone to evaluate different irrigation regimes to optimize mungbean yield. The experiment was arranged in a randomized complete block design (RCBD) with four replications to evaluate eight irrigation regimes *viz.* I_0: Control (no irrigation), I_1: One irrigation at 35 Days After Sowing (DAS), I_2: One irrigation at 45 DAS, I_3: One irrigation at 55 DAS, I_4: Two irrigations at 35 and 45 DAS, I_5: Two irrigations at 35 and 55 DAS, I_6: Two irrigations at 45 and 55 DAS, I_7: Three irrigations at 35, 45, and 55 DAS. The results of the study revealed that the application of three irrigations at 35,45 & 55 Days of Sowing (DAS) resulted in the highest recorded values for key physiological indices, including leaf area index (LAI), crop growth rate (CGR), and total dry matter (TDM) accumulation. Yield and yield attributes were also maximized under the same treatment. Moreover, relative water content (RWC) and chlorophyll concentration were also superior in plots receiving three irrigations, timed specifically at 35,45 & 55 DAS, compared to fewer or no irrigation treatments. A remarkable exception was observed in seed protein content, which was significantly greater in the non-irrigated control treatment compared to all irrigated plots. However, this treatment also resulted in the lowest water use efficiency (WUE), recorded at 2.02 and 1.87 kg ha^{-1} mm^{-1} for the 2018 and 2019 seasons, respectively. In contrast, the three-irrigation regime (35,45 & 55 DAS) demonstrated the highest Water Use Efficiency (3.55 and 3.52 kg ha^{-1} mm^{-1}), establishing it as the most effective strategy for enhancing yield and optimizing water productivity in mungbean cultivation under arid conditions.
Keyword: Mungbean (*Vigna radiata* L.); Irrigation Scheduling; Water Use Efficiency (WUE); Yield Attributes; Arid Region

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1. Introduction

Pulses constitute a fundamental source of plant-based protein in Pakistan, with mungbean (*Vigna radiata* L.) emerging as a critical *kharif* season crop, second only to chickpea in cultivation importance (Imran et al., 2015). Renowned for its nutritional value; providing 24.2% protein, 60.4%

carbohydrates, and 1.3% fat, mungbean also plays a vital role in sustainable agriculture by enhancing soil fertility through atmospheric nitrogen fixation (Basu et al., 2016). Its agronomic advantages, including a short duration (75-90 days), drought tolerance, and adaptability to double cropping systems, make it an ideal candidate for enhancing food security. Recent national data reflect this potential, showing cultivation on 201,000 hectares yielding 153,000 tons, a notable 13.6% increase from the previous year (Pakistan Economic Survey, 2024-25).

Despite this promising output and the availability of improved agronomic practices, a significant yield gap persists between the national average and the crop's genetic potential. This disparity is primarily driven by abiotic stresses, particularly supra-optimal temperatures and acute water scarcity during critical reproductive growth stages. The *kharif* season's high evaporative demand poses a major challenge to soil moisture retention, making precise irrigation management not merely beneficial but essential for maximizing productivity (Decosta et al., 1999). Water stress during flowering and pod-filling phases is profoundly detrimental, leading to reduced pod formation, fewer seeds per pod, diminished seed weight, and consequently, severe yield loss (Mazumder et al., 2003; Siddique et al., 2007; Ranawake et al., 2011). This is especially critical in Pakistan, where water resources are increasingly strained by climate change (Sadeghipour, 2008).

Conversely, strategic irrigation has been demonstrated to significantly mitigate these effects. Supplemental irrigation applied during moisture-sensitive stages can dramatically improve plant water status and yield (Ullah et al., 2020), with evidence indicating that three irrigations can optimize mungbean production (Maqsood et al., 2000). One of the reasons for lower yield is the scarcity of moisture during growth, development and maturity (Asaduzzaman et al., 2008). In this context, deficit irrigation strategies present a viable pathway to maximize water use efficiency (WUE), yield per unit of water applied, which is paramount for sustainable agriculture in arid and semi-arid regions (Postel, 2000).

However, the precise determination of optimal irrigation schedules tailored to specific growth stages remains a key research gap for Pakistani agro-climatic conditions. Therefore, this study was designed to investigate the effects of irrigation timing on yield components and overall water productivity in mungbean. The objective is to identify a deficit irrigation strategy that safeguards yield while optimizing water use, thereby providing a practical solution for farmers in water-limited environments.

2. Materials and Methods

A field study was conducted over two consecutive *kharif* seasons (2018 and 2019) at the Agronomic Research Station in Karor Lal Eason, Layyah, Pakistan. The soil at the experimental site was a sandy loam, with a field capacity of 18.46% and a permanent wilting point of 7.38% by volume. The experiment was arranged in a Randomized Complete Block Design (RCBD) with four replications. The treatments consisted of eight irrigation regimes:

- **I_0:** Control (no irrigation)
- **I_1:** One irrigation at 35 Days After Sowing (DAS)
- **I_2:** One irrigation at 45 DAS
- **I_3:** One irrigation at 55 DAS
- **I_4:** Two irrigations at 35 and 45 DAS
- **I_5:** Two irrigations at 35 and 55 DAS
- **I_6:** Two irrigations at 45 and 55 DAS
- **I_7:** Three irrigations at 35, 45, and 55 DAS

The mungbean variety 'NIAB MUNG-2016' was used as the test crop. A seed rate of 30 kg ha^{-1} was sown with a inter- and intra-row spacing of 30 cm and 10 cm, respectively. The recommended dose of fertilizer (22 kg N ha^{-1} and 57 kg P_2O_5 ha^{-1}) was applied uniformly at sowing using Urea and DiAmmonium Phosphate (DAP) as sources. After emergence, thinning was performed to maintain a uniform plant population of 60 plants per meter row, resulting in a total of 360 plants per plot (plot size: 6 m × 1.8 m = 10.8 m^2). The crop was inter-cultured twice at 30 and 50 DAS for weed control.

Irrigation was applied according to treatment schedules using a cutthroat flume to measure water. For the estimation of soil moisture, initial soil samples were collected at the time of crop sowing and subsequent samplings were carried out at an interval of before applying irrigation till harvest. Soil moisture contents were determined using the gravimetric method by taking samples at 0-15 and 15-30 cm depth. Moisture content was calculated on a dry weight basis after oven drying at 105° C for 24 hours by the following formula.

OW = (WS1 - WS2) x 100 (Standards Association of Australia. 1977)

Where,

OW = Soil moisture percentage on dry weight basis

WS1 = Soil sample weight before oven drying in gm

WS2 = Soil sample weight after oven drying in gm

The depth of irrigation applied to each plot was calculated from the pre-irrigation soil moisture content in the root zone by using the following relationships (Anonymous).

dw = Dr z (Fc – Oi) 100

Where,

d w = depth of water to be applied in mm.

Dr z = depth of root zone in mm.

Fc = Field capacity in percent by volume.

Oi = Soil moisture content before irrigation in percent by volume.

The time required to obtain the desired depth of irrigation for each plot was calculated as reported by Hoffman, et al. 1990 and Rafiq, 2001.

t = K x A x dw q

Where,

t = time required for irrigation in minutes

dw = depth of water to be applied in mm

A = area in m^2

q = discharge in l/sec;

K = constant (1/6 for t in min, dw in mm, A in m^2 and q in l/sec)

The soil samples were taken with the help of Soil Augur up to 0- 15 and 15- 30 cm soil layers for physico-chemical properties (*Table 1*). The soil of the study area was sandy loam in texture having (pH=8.5), low in organic carbon, medium in total nitrogen, phosphorus, and potassium and low in organic matter less than 0.5% (*Table 1*).

The weather data for both growing seasons is as;

Key phenological stages, including days to emergence, 50% flowering, pod formation, and physiological maturity were recorded for each treatment. Ten plants per plot were tagged and monitored daily. A stage was considered attained when 50% of the tagged plants displayed the characteristic feature of that stage.

At harvest, the following data were collected from ten randomly selected plants per plot and averaged: plant height, number of branches per plant, and number of pods per plant. Pod length and the number of grains per pod were determined from a random sample of twenty pods per plot. The net plot area (6 m × 1.8 m) was manually harvested at 90% physiological maturity. The

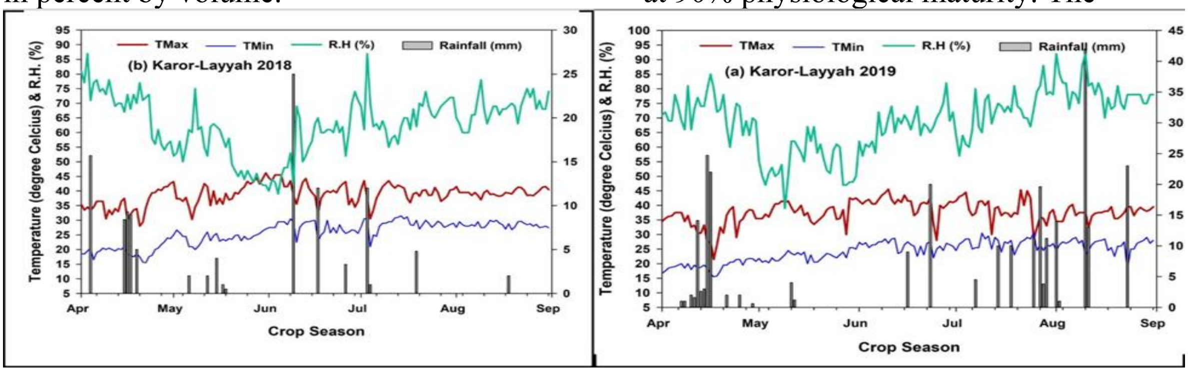

Figure 1: Weather data for both cropping seasons 2018 (left) & 2019 (right).

Table 1: Soil characteristic of experimental sites.

Year	Depth	Sand	Silt	Clay	SOC*	Ec**	pH	***SAR	Texture	N****	P*****	K******
2018	(cm)	%	%	%	%	dS m^{-1}	1:1			gkg^{-1}	ppm	ppm
	0-15	51.3	31.5	14.6	0.48	0.30	8.3	1.16	Sandy loam	0.38	13.26	106
	15-30	50.2	30.5	15.2	0.40	0.35	8.5	1.18	Sandy loam	0.36	8.16	82
2019	0-15	52.4	31.0	14.4	0.46	0.38	8.2	1.04	Sandy loam	0.40	7.82	113
	15-30	52.2	31.2	15.0	0.35	0.42	8.5	1.06	Sandy loam	0.37	5.10	77

*Soil Organic Carbon, **Electrical Conductivity, ***Sodium Absorption Ratio
****Nitrogen, *****Phosphorus, ******Potash

Table 2: Effect of irrigation strategies on phenological stages of mungbean, 2018-2019.

Treatments	**Days to emergence**		**Days to 50% flowering**		**Days to 50% podding**		**Days taken to maturity**	
Irrigation Levels	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**
I_0= control	9.40	9.0	35.0 c	34.0 c	41.0 c	42.0 c	62.5 c	61.0 c
I_1= irrigation at 35 days after sowing	10.0	9.50	38.0 abc	38.0 ab	43.5 bc	43.7 bc	68.2 bc	65.0 bc
I_2= irrigation at 45 days after sowing	11.0	10.0	37.0 abc	37.0 bc	45.0 abc	44.2 bc	69.3 bc	68.0 abc
I_3= irrigation at 55 days after sowing	11.0	10.0	36.0 bc	36.0 bc	44.0 bc	44.7 bc	70.0 abc	67.0 abc
I_4= irrigation at 35,45 days after sowing	10.0	10.2	37.0 abc	39.0 ab	43.0 bc	45.0 abc	69.7abc	68.0 abc
I_5= irrigation at 35,55 days after sowing	10.0	10.0	37.0 abc	38.0 ab	47.0 ab	45.0 abc	72.0 ab	70.0 abc
I_6= irrigation at 45,55 days after sowing	11.0	10.2	39.0 ab	37.0 ab	47.0 ab	46.7 ab	72.0 ab	71.0 ab
I_7= irrigation at 35,45,55 days after sowing	11.0	10.5	40.0 a	41.0 a	48.0 a	49.0 a	75.0 a	74.2 a
SEm±	**0.97**	**0.82**	**0.79**	**0.75**	**1.05**	**1.20**	**1.68**	**2.42**
HSD at 5%	**NS**	**NS**	**2.65**	**2.50**	**3.53**	**4.0**	**5.63**	**8.1**

Table 3: Effect of irrigation strategies on yield related attributes of mungbean, 2018-2019.

Treatments	**Plant height (cm)**		**Pods bearing branches $plant^{-1}$**		**No of pods $plant^{-1}$**		**Pod length (cm)**		**No of seeds pod^{-1}**	
Irrigation Levels	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**
I_0= control	27.0 e	30.0 d	5.0 c	4.4 d	9.10 d	7.7 f	5.1 c	4.3 e	5.0 d	4.4 e
I_1= irrigation at 35 days after sowing	33.0 de	33.0 cd	6.2 c	4.7 d	10.50 d	9.9 ef	6.0 bc	5.1 de	5.7 d	5.2 e
I_2= irrigation at 45 days after sowing	39.17cd	41.0 bcd	8.4 bc	6 bcd	14.0bcd	12.6 cde	6.1 bc	5.4 cde	6.5 cd	5.5 de
I_3= irrigation at 55 days after sowing	38.0 cd	39.0 bcd	7.2 c	5.4 cd	12.0 cd	10.5 def	6.3 bc	5.5 cde	7.0 bcd	5.8 cde
I_4= irrigation at 35,45 days after sowing	42.0 bc	44.0 abc	7.0 c	6.4bcd	16.0bcd	14.2 bcd	7.0 abc	6.4 bcd	7.3 bcd	6.7 bcd
I_5= irrigation at 35,55 days after sowing	49.0 ab	50.3 ab	10 abc	7.2abc	20.0abc	15.6 bc	7.5 ab	7.0 bc	9.0 abc	7.2 abc
I_6= irrigation at 45,55 days after sowing	47 abc	49.0 ab	12 ab	7.4 ab	23.0 ab	17.1 ab	8.0 ab	7.4 ab	9.5 ab	7.8 ab

I_7= irrigation at 35,45,55 days after sowing	53.50 a	55.0 a	13.0 a	8.7 a	26.0 a	19.5 a	9.0 a	8.8 a	10.5 a	8.5 a
SEm±	**4.0**	**2.60**	**1.23**	**0.60**	**2.50**	**1.11**	**0.58**	**0.53**	**0.87**	**0.44**
HSD at 5%	**8.7**	**13.52**	**4.14**	**2.0**	**8.39**	**3.7**	**1.97**	**1.77**	**2.9**	**1.4**

harvested plants were sun-dried for 24 hours and weighed to determine biological yield. After threshing, the grain yield was recorded. The harvest index (HI) was calculated as follows:

HI = (Grain Yield / Biological Yield) × 100

A random sample of seeds from each plot was used to determine the 1000-seed weight. Chlorophyll density was measured on three fully expanded leaves from three randomly selected plants per plot at 20 days after flowering using a Minolta SPAD-502 meter. Values are expressed in SPAD units.

The third fully expanded leaf from the top of selected plants was sampled between 8:30 and 10:30 AM. Fresh weight (FW) was recorded immediately. Leaves were then hydrated to full turgidity for 3 hours to record turgid weight (TW), followed by oven-drying at 80°C to determine dry weight (DW). RWC was calculated as:

RWC (%) = [(FW - DW) / (TW - DW)] × 100

The crude protein content of mungbean seeds was determined using the standard macro-Kjeldahl method (AOAC, 2000; Method 984.13). A finely ground sample (~0.5 g) was digested in concentrated sulfuric acid with a potassium sulfate/copper sulfate catalyst. The digested sample was distilled after alkalization with 40% NaOH, and the liberated ammonia was collected in a boric acid solution. The ammonium borate was titrated with standardized 0.1 N HCl. Percentage nitrogen was calculated from the titration data and multiplied by a conversion factor of 6.25 to obtain crude protein content.

Plants from a defined unit area were harvested, and their leaves were detached. The total leaf area was measured using a leaf area meter (Model CI-202, CID, Inc., USA). LAI was calculated as the ratio of total leaf area (m^2) to the ground area (m^2) from which the plants were sampled (Watson, 1947).

Plant samples were sun-dried for 24 hours and then oven-dried at 75°C for 48 hours until a constant weight was achieved. TDM was recorded as the dry weight per unit ground area (g m^{-2}).

CGR was calculated from the accumulated dry matter between two consecutive harvests using the formula described by Hunt (1978):

Table 4: Effect of irrigation strategies on 1000 g. wt., biological yield, seed yield and harvest index of mungbean, 2018-2019.

Treatments	**1000-g. wt (g)**		**Biological yield (kg / ha^{-1})**		**Seed yield (kg / ha^{-1})**		**Harvest index (%)**	
Irrigation Levels	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**
I_0= control	33.5 c	30.80 f	1470.9 e	1259.3 f	360.2 f	322.0 f	24.46 ab	25.57 ab
I_1= irrigation at 35 days after sowing	37.0 bc	35.72 e	1746.7e	2074.1 e	445.7 ef	369.7 ef	25.61 ab	17.90 c
I_2= irrigation at 45 days after sowing	38.1 bc	36.96 de	2745.6 d	2585.6 d	552.6 de	457.3 ef	20.12 b	17.67 c
I_3= irrigation at 55 days after sowing	41.0 abc	38.52 cde	2630.3 d	2391.2 de	581.2 de	515.5 de	22.14 ab	21.54 bc
I_4= irrigation at 35,45 days after sowing	42.4 ab	39.97 bcd	3238.9 c	2944.4 c	690.4 cd	640.0 cd	21.28 b	21.74 bc

I_5= irrigation at 35,55 days after sowing	44.6 ab	41.04 abc	3418.9 bc	3046.3 bc	802.3 bc	761.9 bc	23.46 ab	25.03 ab
I_6= irrigation at 45,55 days after sowing	45.1 ab	42.09 ab	3694.8 b	3368.0 ab	900.4 b	835.9 b	24.35 ab	24.85 ab
I_7= irrigation at 35,45,55 days after sowing	47.0 a	43.63 a	4069.0 a	3699.0 a	1112.0 a	1028.0 a	27.32 a	27.84 a
SEm±	**2.53**	**1.90**	**96.77**	**99.34**	**47.40**	**40.50**	**1.53**	**1.31**
HSD at 5%	**8.51**	**3.0**	**324.600**	**333.244**	**184.18**	**162.06**	**5.59**	**5.76**

Table 5. Water use efficiency of mungbean under different irrigation strategies, 2018-2019.

Treatments	**No of irrigation**		**total water use (mm)**		**WUE (kg ha^{-1} mm^{-1})**	
Year	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**
I_0	0	0	178	172	2.02	1.87
I_1	1	1	214	207	2.08	1.92
I_2	1	1	220	211	2.50	2.16
I_3	1	1	228	219	2.54	2.35
I_4	2	2	265	254	2.60	2.51
I_5	2	2	280	262	2.86	2.90
I_6	2	2	287	267	3.13	3.12
I_7	3	3	313	292	3.55	3.52

I_0 = No irrigation, I_1 = Irrigation at flowering stage, I_2 = Irrigation at pod setting stage, I_3 = Irrigation at pod filling stage, I_4 = Irrigation at 1st flowering stage + pod setting stage, I_5 = Irrigation at 1st flowering stage + pod filling stage, I_6 = Irrigation at pod setting stage + pod filling stage, I_7 = Irrigation at flowering stage + pod setting stage + pod filling stage.

Table 6. Effect of irrigation strategies on relative water content, chlorophyll content and protein content of mungbean 2018-2019.

Treatments	**Relative water content (%)**		**Chlorophyll content (%)**		**Protein content (%)**	
Irrigation Levels	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**
I_0= control	34.0 e	32.77 e	41.30 c	39.16 e	23.0 a	23.21 a
I_1= irrigation at 35 days after sowing	46.0 de	41.49 de	43.10 bc	39.80 e	22.43 a	23.65 a
I_2= irrigation at 45 days after sowing	47.4 de	48.84 cd	43.25 bc	41.25 de	21.15 ab	21.79 ab
I_3= irrigation at 55 days after sowing	51.4 cd	49.90 bcd	44.20 abc	41.78 cde	21.34 ab	21.78 ab
I_4= irrigation at 35,45 days after sowing	60.1 bcd	58.74 abc	44.16 abc	43.10 bcd	22.0 ab	22.33 ab
I_5= irrigation at 35,55 days after sowing	66.0 abc	63.81 ab	49.21 ab	44.70 bc	21.43 ab	22.66 ab
I_6= irrigation at 45,55 days after sowing	71.0 ab	67.57 ab	50.0 ab	45.60 b	20.46 bc	20.18 bc
I_7= irrigation at 35,45,55 days after sowing	77.0 a	72.93 a	51.6 a	49.50 a	19.30 c	19.96 c
SEm±	**4.68**	**4.42**	**2.16**	**0.99**	**1.22**	**1.03**
HSD at 5%	**15.7**	**14.8**	**7.26**	**3.3**	**1.21**	**1.34**

CGR = $(W_2 - W_1) / (t_2 - t_1)$ where W_1 and W_2 are the total dry matter (g m^{-2}) at times t_1 and t_2 (in days), respectively. WUE was calculated for grain yield according to the method described by Howell (2001):

WUE (kg ha^{-1} mm^{-1}) = Grain Yield (kg ha^{-1}) / Total Water Consumed (mm)

The parameters under investigation were statistically analyzed using a randomized complete block design with four replications. The various variables of irrigation treatments were statistically analyzed using Fisher's analysis of variance techniques. The variations between treatment means were compared using the Honest Significant Difference (HSD) test at a 5% probability level (Steel et al., 1997). Statistix version 8.1 software computer base was used to done the statistical analysis (Statistix, analytical Software, USA, 1985-2003).

3. Results and Discussion

Phenological Parameters: Irrigation treatments significantly influenced all recorded phenological stages (days to 50% flowering, 50% podding, and physiological maturity) during both the 2018 and 2019 (Table 3) study seasons, with the exception of days to emergence, which showed no significant variation. The treatment receiving three irrigations (I_7: applied at flowering, pod formation, and pod filling) exhibited a significantly prolonged phenological period, taking the highest number of days to reach 50% flowering (40.0-41.0 days), 50% podding (48.0-49.0 days), and maturity (74.0-75.0 days). These results were statistically similar to those of the two-irrigation treatments I_5 (flowering & pod filling) and I_6 (pod formation & pod filling). In contrast, the control treatment (I_0: no irrigation) consistently resulted in the shortest phenological period, accelerating development across all stages.

Yield Related Parameters: Seed yield, biological yield, and all yield-related attributes were significantly affected by irrigation treatments in both years (Table 3, 5). The highest seed yield (1112.0 and 1028.0 kg ha^{-1}) and biological yield (4069.0 and 3699.0 kg ha^{-1}) were achieved with the I_7 treatment (three irrigations). This was significantly superior to all other treatments. The lowest yields were recorded in the control treatment (I_0: 360 and 322 kg ha^{-1} seed yield; 1470 and 1259 kg ha^{-1} biological yield), which was statistically on par with the single irrigation treatment at flowering (I_1).

All yield components followed a similar trend. The maximum values for plant height (53.50-55.0 cm), pods bearing branches per plant (9.7-13.0), pods per plant (19.5-26.0), grains per pod (8.5-10.5), pod length (8.8-9.0 cm), and 1000-grain weight (43.6-47.0 g) were observed in the I_7 treatment. These results were statistically comparable to those from the two-irrigation treatments I_5 and I_6. The control plot (I_0) consistently produced the minimum values for all these traits. The harvest index was also greatest in the I_7 treatment (27.30-27.84%), which was statistically at par with I_5 and I_6, and lowest in the control (24.46-25.75%).

Water Use Efficiency: Water use efficiency (WUE) was significantly influenced by irrigation treatments. The highest WUE (3.52-3.55 kg ha^{-1} mm^{-1}) was achieved with the I_7 treatment, followed by the two-irrigation treatments I_6 and I_5. The lowest WUE (1.87-2.02 kg ha^{-1} mm^{-1}) was recorded in the control treatment (I_0), a consequence of its severely reduced seed yield.

Physiological Parameters

Relative Leaf Water Content (%): Relative water content (RWC) was significantly influenced by irrigation treatments. The highest RWC (72.93-77.0%) was recorded in the I_7 treatment, which was statistically similar to treatments I_5 (63.8-66.0%) and I_6 (65.57-71.0%). The control treatment (I_0) resulted in the lowest RWC (32.77-34.0%).

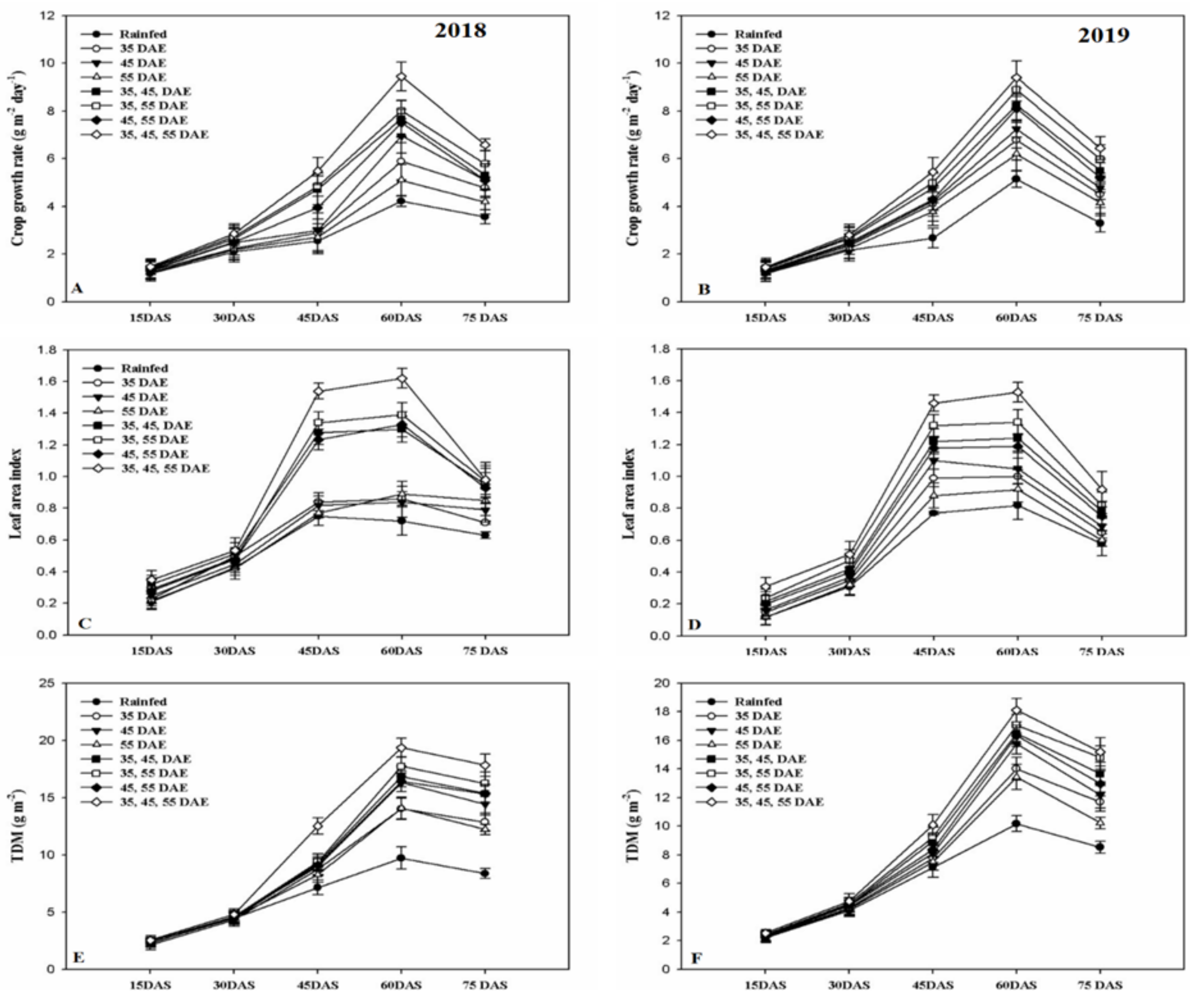

Figure 2: Growth dynamics of mungbean (*Vigna radiata L.*) under different irrigation regimes across the 2018 (left) and 2019 (right) kharif seasons.

Chlorophyll Contents (SPAD Units): Chlorophyll content was significantly affected by irrigation. The I_7 treatment produced the highest chlorophyll readings (49.50-51.60 SPAD units), which were statistically on par with treatment I_6 (45.60-50.0 SPAD units). The minimum chlorophyll content (39.16-41.30 SPAD units) was recorded in the control plot (I_0).

Biochemical Parameters

Protein Contents: Protein content was significantly influenced by irrigation treatments during both experimental years. Contrary to the trend observed in yield parameters, the greatest protein content (23.0 - 23.21%) was recorded in the non-irrigated control treatment (I_0). This result was statistically similar to the treatment receiving a single irrigation at flowering (I_1). Conversely, the lowest protein content (19.30 - 19.96%) was found in the I_7 treatment, which received three irrigations at flowering, pod setting, and pod filling stages.

Crop Growth Parameters

Crop growth parameters, Crop Growth Rate (CGR), Leaf Area Index (LAI), and Total Dry Matter (TDM) were significantly affected by irrigation treatments in both 2018 and 2019. All three parameters increased with plant age and were positively correlated with irrigation frequency. The highest values for CGR, LAI, and TDM were consistently observed in the I_7 treatment (three irrigations), while the lowest values were recorded in the non-irrigated control (I_0).

The graphical representation of the data (Fig. 2) revealed a consistent physiological pattern across treatments:

CGR and LAI increased until approximately 60 Days after Sowing (DAS), after which they declined as the crop approached physiological maturity (75 DAS). TDM accumulation increased sharply between 45 and 60 DAS, followed by a decline from 60 DAS until harvest, indicative of biomass partitioning to developing grains during the reproductive stages.

4. Discussion

The results of this two-year study demonstrate that irrigation scheduling significantly influences the phenology, growth, yield, and physiological responses of mungbean. The extended phenological period observed under full irrigation (I_7) can be attributed to the sustained availability of soil moisture, which delays senescence and supports a longer developmental cycle compared to the accelerated maturation induced by water stress in deficit treatments (I_0, I_1). This finding aligns with the work of Sisay et al. (2014) and Uddin et al. (2013), who reported that water deficit accelerates phenological development in pulses.

Superior plant height, yield components, and ultimate seed and biological yield under the three-irrigation regime (I_7) are likely a direct consequence of maintained turgor pressure, facilitating cell expansion, uninterrupted nutrient translocation, and sustained photosynthetic activity throughout the critical reproductive phases. Ample soil moisture minimizes abiotic stress, allowing for optimal expression of genetic yield potential, as supported by the findings of Ram et al. (2016) and Karande et al. (2019). Conversely, the severe yield reduction in the non-irrigated control (I_0) underscores the detrimental impact of water stress on fundamental physiological processes like photosynthesis and metabolite partitioning, consistent with the observations of Islam et al. (2021).

The enhanced chlorophyll content and relative water content (RWC) in well-irrigated plants (I_7) indicate robust physiological health and an enhanced capacity to mitigate heat stress through transpirational cooling, as noted by Allahmoradi et al. (2011). The inverse relationship between irrigation frequency and seed protein content, however, presents a notable trade-off. The higher protein concentration in stressed plants (I_0) is likely a result of the concentration effect due to reduced carbohydrate accumulation and the accumulation of nitrogenous compounds like proline and other free amino acids that are not synthesized into proteins under stress, a phenomenon previously documented by Mujtaba and Alam (2002).

The highest water use efficiency (WUE) achieved with three irrigations (I_7) demonstrates that the increased yield more than compensates for the additional water input, representing the most efficient and productive use of a limited water resource. This efficient translation of water into biomass and grain (CGR, TDM, LAI) under optimal irrigation highlights the severe growth constraints imposed by water deficit, as reported by Mondal et al. (2012).

5. Conclusion

This study establishes that the strategic timing of irrigation is more critical than the total water volume for optimizing mungbean production in arid regions. Our key finding—the significant yield increase (approximately 30%) achieved with three well-timed irrigations at the reproductive stages (35, 45, and 55 days after sowing)—provides a clear, practical blueprint for farmers. The novelty of this work lies in precisely quantifying the yield trade-offs of deficit irrigation, confirming that while it can enhance seed protein concentration, the associated yield penalty is economically prohibitive. For practical recommendation, we strongly advocate for the I7 irrigation schedule (three irrigations at 35, 45, and 55 DAS) as the most effective strategy to maximize both yield and water use efficiency in similar agro-climatic zones. This approach directly counters the prevalent practice of drought avoidance through early maturation, demonstrating that securing moisture throughout the critical reproductive window is paramount. Future research should focus on validating these irrigation schedules across a wider range of soil types and climates, integrating them with drought-tolerant mungbean varieties, and conducting a detailed economic analysis to further solidify adoption incentives for smallholder farmers.

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