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Optimizing Irrigation Strategies for Wheat in Sindh: Balancing Yield, Water Use Efficiency, and Water Footprint

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Water scarcity jeopardizes food production in arid and semi-arid regions, making efficient irrigation crucial to enhance water use efficiency (WUE) and sustain crop yields. Thus, a study was conducted to measure the impact of three furrow irrigation methods (FIM) [conventional furrow irrigation (CFI), alternate furrow irrigation (AFI), and fixed furrow irrigation (FFI)] combined with three different irrigation levels (IL) (100%; 80%, and 60% crop water requirement) on crop growth, yield attributes, grain yield, biomass, WUE, and blue water footprint of wheat crop during the Rabi season 2022-2023 in Tandojam, Hyderabad. Treatments were arranged in a randomized complete block design (RCBD) with three replications. Results illustrated that FIMs and ILs had a substantial ($P < 0.05$) effect on the crop growth, yield attributes, grain yield, and biomass, while their interaction had no substantial effect ($P > 0.05$). Compared with AFI and FFI, CFI had substantially higher grain yield (11.1-15.3%) and biomass (5.0-12.3%), lower WUE (1.23-31.86%), and higher blue water footprint (41.7-46.7%). Whereas AFI compared with CFI saved water by 39.13%, improved WUE by 31.86%, and lowered blue water footprint by 29.86%, with a moderate yield decrease (13.22%) at 80% crop water requirement. Therefore, AFI combined with an 80% crop water requirement is recommended as an efficient irrigation strategy for wheat in water-scarce areas.

Keywords: furrow irrigation methods; irrigation levels; water use efficiency; water footprint; wheat yield

Introduction:

Global groundwater depletion is being rapidly intensified by climate change and unsustainable agricultural practices, a situation that is particularly acute in developing Asian nations. In these regions, groundwater loss plays a major role in causing water shortages for crop irrigation, especially during dry spells [1][2]. Climate change and increasing water scarcity are introducing significant challenges to effective irrigation management. As water demand rises, climate change also threatens crop productivity. Implementing efficient irrigation strategies is crucial to mitigate these negative impacts and promote the sustainable use of water resources [3].

Freshwater scarcity, primarily driven by accelerating groundwater depletion, has emerged as a pressing environmental concern, directly threatening global food security through its adverse effects on sustainable crop production [4][5]. Agriculture accounts for the highest proportion of freshwater use globally, and the diminishing availability of this critical resource, exacerbated by rapid population growth, industrialization, climate change, and inefficient irrigation practices, poses a significant challenge to long-term agricultural sustainability [6][7].

Irrigation, through river diversions or groundwater pumping, enhances crop yields, especially in areas with insufficient rainfall. Although only about 18% of the world's arable land is irrigated, it accounts for 70% of global gross blue water withdrawals and 92% of net blue water use, contributing to roughly 40% of global crop production [8][9].

Worldwide, diverse strategies have been implemented to maximize the efficient use of available water resources. Among these, deficit irrigation has emerged as a promising technique, capable of conserving up to 12% of total water input while enhancing water productivity compared to full irrigation [10]. The deficit irrigation operates by strategically limiting water application to maintain acceptable yield levels, aligning water supply with the crop's critical growth stages based on the principle of diminishing returns [11]. This method entails providing irrigation water in amounts below the full crop evapotranspiration (ET) demand, which in turn improves water use efficiency (WUE). Research suggests that optimal deficit irrigation application typically ranges between 60% and 100% of the crop's ET demand [12]. The WUE tends to improve under deficit irrigation compared to full irrigation, as moderate water applications increase crop ET and consequently yield in a nearly linear manner up to a certain threshold. Beyond that point, additional irrigation contributes little to no further yield improvement. However, many farmers continue to over-irrigate in pursuit of higher yields, which exacerbates inefficient water use and intensifies the global challenge of freshwater scarcity [13].

The conventional furrow irrigation method (CFI), being highly water-intensive where each furrow is irrigated during every irrigation, contributes to the overuse of freshwater resources. The CFI uses more water and typically results in lower crop yields compared to drip irrigation systems [14][15]. To maintain efficiency and safeguard the environment without compromising crop yield and quality, it is essential to integrate water-saving strategies into its operation [16]. The potential for reducing water losses exists in alternate furrow irrigation (AFI), where two adjacent furrows receive irrigation interchangeably during successive watering periods, and fixed furrow irrigation (FFI), where only one furrow is irrigated, while the adjacent one remains dry throughout the growth period. The significance of WUE is particularly growing in arid and semi-arid areas to enhance water management practices. In arid and semi-arid regions, nearly all crop production relies on irrigation, with furrow irrigation being the predominant method. However, furrow irrigation is characterized by low application efficiency (45–60%), resulting in significant water losses primarily due to excessive application, leading to deep percolation from the irrigated area [17]. To optimize the use of limited water resources, substantial modifications to the CFI system are necessary. Research conducted by authors [18] demonstrated that FFI conserved water and yielded comparable results to the CFI. Author [19] reported that AFI used less irrigation water but maintained similar grain yield production to that of CFI. AFI was proposed as a method to enhance WUE and decrease chemical leaching compared to CFI, with minimal yield losses compared to FFI for various crops [20]. In the context of maize cultivation, AFI reduced water consumption by 35%, accompanied by a total biomass reduction of 6-11% compared to fully watered plants [21].

Several indicators are used to assess water efficiency, with the most common being WUE and water footprint. WUE measures crop yield per unit of water consumed ($t\ m^{-3}$), whereas the water footprint indicates the volume of water used per unit of production ($m^3\ t^{-1}$). WUE assesses crop output concerning the total water lost to the atmosphere, while the water footprint quantifies water loss per unit of crop produced [22]. WUE combines green and blue water use into a single value, while water footprint distinguishes between them: green water footprint measures rainwater uses per unit of crop, and blue water footprint measures irrigation water use. Together, they form the consumptive water footprint. A third component, gray water footprint, represents water pollution per crop unit, but it is excluded here as the focus is on water use, not pollution. These indicators also differ in defining water loss. WUE and water footprint treat all evapotranspiration whether from transpiration (T) or evaporation (E), and whether from rain (green) or irrigation (blue) as loss, since this water exits the system and is no longer reusable [23]. The crop water footprint offers a detailed evaluation of how efficiently water resources are used in agriculture by accounting for the total water consumed throughout a crop's growth period [24]. Unlike conventional approaches to assessing agricultural water use, the crop water footprint method allows for more precise estimation of crop water requirements and supports evidence-based strategies for managing water in agriculture [25][26]. At present, research on water footprints continues to attract significant academic interest, with most studies concentrating on their quantification. However, relatively few investigations have addressed the sustainability of agricultural water resources by examining how water footprints relate to actual agricultural water use particularly in dry regions.

Wheat (Triticum aestivum L.) holds a significant position as a major global food grain crop, playing a crucial role in the staple diet of approximately one-third of the world's population, including Pakistan. In Pakistan, wheat cultivation spans an extensive area of 8.9 million hectares, resulting in an annual production of around 26.394 million tons in the 2021-22 period, with an average yield of 3.0 t ha^{-1} [27]. Sindh produced about 3.8 million tons of grains (14.24% of the whole country) during the Rabi season 2021-22 [28]. Regardless of its elevated yield potential, the average wheat yield in Pakistan falls below that of most countries worldwide. Wheat holds the top position among cereal crops in Pakistan, covering approximately 66% of the annual cultivated land for food crops [29].

Various factors contribute to the low grain yield of wheat, including temperature fluctuations, insufficient irrigation water, inadequate plant nutrients, weed competition, insect attacks, and disease infections. Among these, lack of irrigation water accounts for approximately 30% of wheat production losses, while nutrient deficiencies and soil metal content contribute to a 40% yield reduction, along with other environmental factors [30][31]. Conversely, adequate irrigation water and nutrient supply have the potential to increase wheat yield by up to 70% [30]. The frequency of irrigation plays a crucial role in wheat growth and yield. Increasing irrigation frequencies have been shown to positively impact wheat grain yield [32]. It has been demonstrated that AFI reduced deep percolation and soil surface evaporation, requiring less irrigation water than full irrigation, while maintaining a comparable yield. As a result, WUE has shown improvement in AFI compared to CFI [33]. Limited information is available regarding the impact of different furrow irrigation techniques and varying irrigation levels on the growth and yield of wheat crops. Therefore, this study was conducted with the specific aim of evaluating different agricultural management practices on the growth, yield, WUE, and blue water footprint of wheat crops.

Objectives and Novelty Statement of the Study:

The study aimed to evaluate the effect of different furrow irrigation methods and irrigation water levels on the growth of the wheat crop, yield attributes, grain yield, crop water productivity, and blue water footprint of the wheat crop. This study uniquely integrates three furrow irrigation methods with varying irrigation levels to evaluate their combined effects on wheat yield, water use efficiency, and blue water footprint in arid conditions. It identifies AFI at 80% crop water requirement as a water-saving strategy with minimal yield loss and water footprint, offering a practical solution for sustainable wheat production in water-scarce regions.

Materials and Methods:

Field Study Site:

The experiment was conducted at Barley and Wheat Research Institute, Tandojam, during the Rabi season of 2022-23. This region has an altitude of 23 m above sea level at 25º24' 59.364" N latitude and 68º32' 39.696" E longitude. The experimental site climatically falls in the arid and semi-arid climate. The minimum and maximum temperatures were 5.1℃ and 37.9 ℃ from November to March, respectively (Fig. 1a). There was no rainfall recorded in the growing season. Relative humidity and wind speed ranged from 18.9-58.4% and 7.9-44.8 m s^{-1}, respectively (Fig. 1b). Sunshine hours and solar radiation ranged from 10.6-12.4 h and 12.6-22 MJ m^{-2} d^{-1}, respectively.

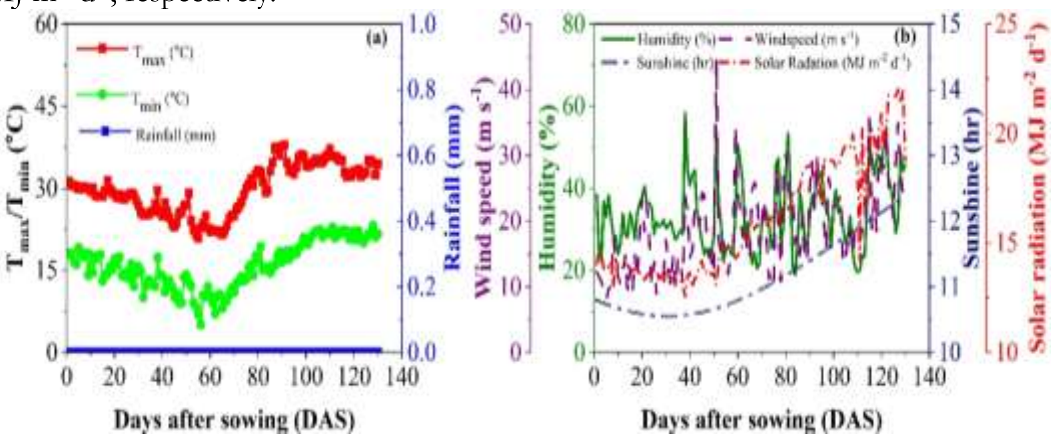

Figure 1. (a) Daily values of maximum temperature (T_{max}, ℃), minimum temperature (T_{min}, ℃), rainfall (mm), and **(b)** humidity (%), windspeed (m s^{-1}), sunshine (h), and solar radiation (MJ m^{-2} d^{-1}) at the experimental site throughout the growing season

Experimental Layout and Design:

The field was prepared using a cultivator and then properly leveled with a tractor-drawn leveler. Furrows were created manually. In this research experiment, the wheat variety TD-1 was sown in the third week of November 2022 at a rate of 124 kg ha^{-1}. Chemical fertilizers such as NPK were applied to the wheat crop at the rate of 120: 90: 60 kg ha^{-1} [34]. The entire quantity of P and K, and half of N, was applied once as a basal dose during the land preparation for seed sowing. The remaining N was applied at the time of the 1st and 2nd irrigations in equal amounts. The weeds were removed manually in all treatments. Irrigation water was applied when the soil water content dropped to 50-55% of the field capacity [35].

The treatments included three different furrow irrigation methods (FIM) as CFI, AFI, and FFI, and three irrigation levels (IL) such as 100% of crop water requirement (W1), 80% of crop water requirement (W2), and 60% of crop water requirement (W3). The total area of the experimental plot was 36 m × 12 m (432 m^2). The unit plot size was 3 m × 3 m with 1m buffer distance between all the plots (Fig. 2). Furrows were spaced 0.3 m apart, with a depth maintained between 0.2 and 0.3 m. The experiment was conducted using a randomized complete block design (RCBD), where each treatment consisted of a combination of irrigation method and irrigation level. In total, nine treatments were deployed in the study. Each treatment was replicated three times. The treatments were labelled as follows: CFIW1, CFIW2, and CFIW3 represented CFI applied at 100%, 80%, and 60% of the crop water requirement, respectively; AFIW1, AFIW2, and AFIW3 corresponded to AFI at 100%, 80%, and 60% of crop water requirement, respectively; and FFIW1, FFIW2, and FFIW3 denoted FFI with 100%, 80%, and 60% of crop water requirement, respectively. Figure 3 illustrates the detailed methodology flow chart of the study.

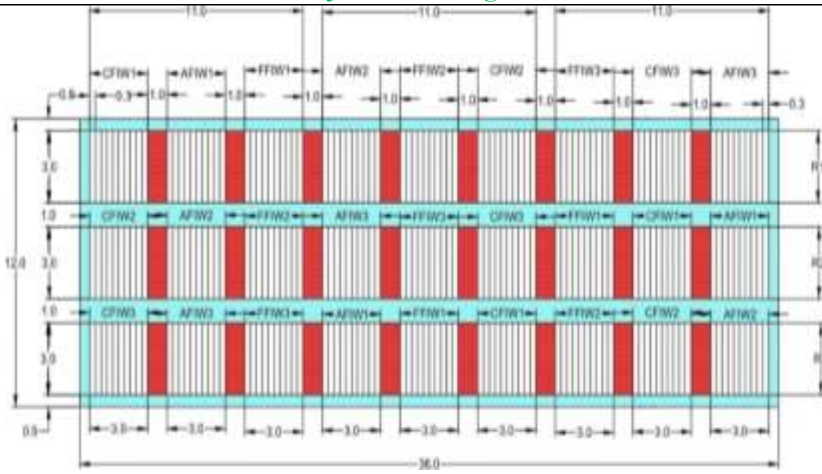

Figure 2. Layout of the experimental field

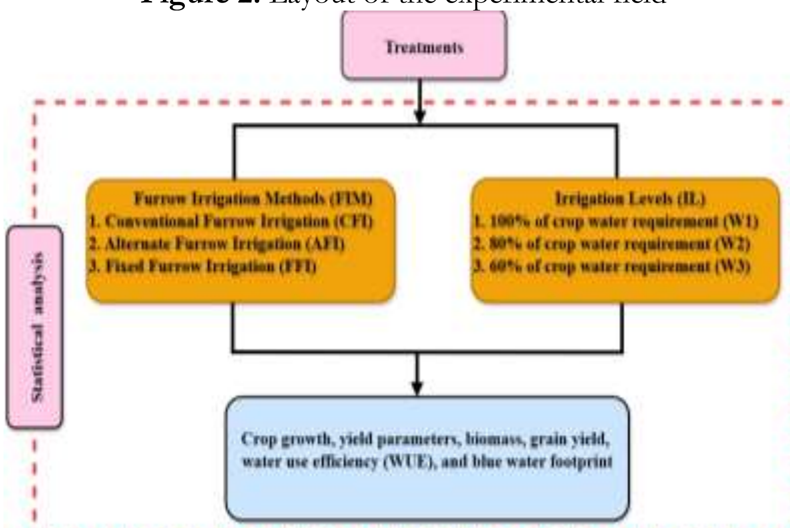

Figure 3. Flow chart of the methodology

Soil Sampling:

The composite soil samples were collected at soil depths 0-20 cm, 20-40 cm, and 40-60 cm before sowing of the crop. The soil physico-chemical properties were measured in the laboratory of the Department of Land and Water Management, Faculty of Agricultural Engineering and Technology, Sindh Agriculture University, Tandojam. Soil texture was determined using the Bouyoucos hydrometer method [36], while dry density was measured by the core sampler method [37]. Soil was collected from the field with the help of a core sampler, and then the sample was dried in an oven for 24 hours at 105 ℃. Dry density was calculated by using equation (1).

$$\rho_d = \frac{W_s}{V_s} \quad (1)$$

Where ρ_d is dry density (g cm^{-3}), W_s is the weight of dry soil (g), and V_s is the volume of solid soil (cm^{-3}).

The pH of the soil sample was determined by a pH meter, using the electrochemical method [38]. The electrical conductivity of the soil (EC_e) of the soil sample was determined by an EC meter, using the electrochemical method [38]. Soil nitrogen and phosphorus of the soil sample were determined by colorimeter using the Naver 5 method. Potassium in soil samples was analyzed by the flame photometer method.

Table 1 provides information about the particle size distribution, texture class, and dry density for each depth range of the experimental site. The soil texture class of the experimental field was silty clay loam. Additionally, the dry density of the soil slightly varies from 1.27-1.28

g cm^{-3} from 0-60 cm depth. The mean bulk density for the 0–60 cm soil depth was measured at 1.27 g cm^{-3}. The average soil pH and electrical conductivity (ECe) within the same layer were 8.54 and 1.5 dS m^{-1}, respectively (Table 1). The available soil nitrogen (N), phosphorus (P), and potassium (K) concentrations in the 0–60 cm soil layer were 2.1 mg kg^{-1}, 8.78 mg kg^{-1}, and 6.5 mg kg^{-1}, respectively.

Table 1. Physical and chemical properties of the soil

Sampling Depth (cm)		0-20	20-40	40-60	Mean
Particle Size distribution (%)	Clay	32.3	30.4	30.3	31.0
	Silt	62.5	65.4	64.6	64.16
	Sand	5.2	4.2	5.1	4.83
Soil texture class	Silty clay loam	Silty clay loam	Silty clay loam	Silty clay loam	Soil texture class
Dry density (g cm^{-3})		1.27	1.27	1.28	1.27
Soil pH (1:2.5)		8.46	8.55	8.61	8.54
EC_e (dS m^{-1})		1.48	1.5	1.50	1.50
Available N (mg kg^{-1})		2.2	2.0	2.1	2.1
Available P (mg kg^{-1})		8.78	8.80	8.77	8.78
Available K (mg kg^{-1})		6.6	6.4	6.5	6.5

Measurement of Various Growth Parameters:

Plant height was measured fortnightly using a measurement tape from the bottom to the tip of the randomly selected plants in each plot and averaged in centimeters [39]. The number of tillers per meter of row was counted every fortnight from a fixed 1-meter row segment, starting after the first irrigation and continuing until harvest. For every treatment, three replications were sampled from a 1m row length. Above-ground biomass was measured by sampling 15 plants randomly from each plot fortnightly. The plant materials were dried in an oven at 70℃ for 24 h and then weighed [39].

Measurement of Yield Parameters, Biomass, and Grain Yield:

Crop harvesting was done manually at maturity state and collected grain yield, straw yield, effective tillers, and 1000-grain weight. The predetermined 1m crop row length prior to the irrigation treatment started was harvested manually and wrapped carefully in paper so that no grains or plants were damaged. Post-harvest parameters namely panicle length, number of spikes per panicle, and number of grains per panicle were measured on 10 randomly selected plants from the 1-meter sample. Whereas the effective and non-effective tillers were measured from a 1m^2 crop sample by identifying the number of filled ear-heads (panicles) and unfilled ear-heads (panicles), respectively, before threshing the samples. After threshing the experimental crop for each plot separately, 1000-grain from each plot was taken and weighed by an electronic top-loading balance in grams. At maturity, the wheat crop in each plot was harvested, and the biomass and grain yield were weighed using an electronic balance.

Water use efficiency, water saving, and blue water footprint:

Water use efficiency (WUE) was calculated using equation (2).

$$\text{WUE (kg m}^{-3}) = \frac{\text{crop yield (kg ha}^{-1})}{\text{Evapotranspiration (m}^3\text{ ha}^{-1})} \quad (2)$$

Evapotranspiration is the total irrigation water supplied during the experimental period.

The water saving (%) in AFI and FFI, compared to CFI, was calculated using equation (3) [40].

$$\text{water saving (\%)} = \frac{W_{CFI} - W_{AFI} \text{ or } W_{FFI}}{W_{CFI}} \times 100 \quad (3)$$

Where W_{CFI}, W_{AFI}, and W_{FFI} are the total water used in the CFI, AFI, and FFI methods (m^3 ha^{-1}), respectively.

The blue water footprint was calculated using equation (4) [41].

$$\text{Blue water footprint } \frac{CWU_{blue}}{\text{crop yield (kg ha}^{-1})} \quad (4)$$

Where CWU_{blue} is the blue water component of the crop ($m^3\ t^{-1}$), yield calculated as in equation (5).

$$CWU_{blue} = 10 \times \sum_{d=1}^{LGP} ET_{blue} \quad (5)$$

Where ET_{blue} represents the evapotranspiration of blue water, which refers to the water lost through evapotranspiration from irrigation water consumed by plants (mm) in a season. The factor 10 is used to convert this water depth (in mm) into the volume of water per hectare ($m^3\ ha^{-1}$). LGP stands for the length of the growing period, measured in days. Therefore, summing the daily evapotranspiration values over the entire growing period gives the total evapotranspiration from planting to harvest. The CWU_{blue} indicates the amount of irrigation water directly used by the plant to meet its water needs.

Crop Water Requirement:

The United Nations Food and Agriculture Organization (FAO) developed the CROPWAT model (version 8.0), which requires climatic, soil, and crop data for its operation. Climatic data were obtained from the local weather station and included minimum and maximum temperatures, relative humidity, wind speed, and sunshine hours (Table 2). The effective rainfall was calculated using the USDA soil conservation service method, which utilized the total rainfall value (Table 3). Soil and crop data measured in the study area were employed in the CROPWAT (Tables 4 and 5). The reference evapotranspiration (ETo) for the wheat crop was calculated using the Penman-Monteith equation, based on agro-climatic data. The CROPWAT model was used to calculate the total crop water requirement of the wheat crop in this study (Table 6). The total crop water requirement for the wheat crop was 450 mm. Thus, 100% crop water requirement (W1) was considered 450 mm, 80% (W2) 360 mm, and 60% (W3) 270 mm.

Irrigation:

A cutthroat flume (8" × 1.5') was installed at the center of the watercourse to apply the required depth of water to all replicated plots [42]. The time required to apply the necessary depth of water was calculated using Equation (6) [43].

$$Q \times T = A \times D \quad (6)$$

Where Q is the discharge required (m^3), T is the time of application (h), A is the area to be irrigated (ha), and D is the depth of irrigation to be applied (m).

Statistical Analysis:

The SPSS 24.0 (SPSS Inc., Chicago, III, USA) statistical software was used for analysis of variance (ANOVA). The FIMs and ILs means were separated using Duncan's multiple range test at $P < 0.05$.

Results:

Applied Irrigation Depth:

Irrigation was applied at regular 21-day intervals for all treatments, specifically on the 21, 42, 63, 84, and 105 days after sowing (DAS) (Table 7). Before sowing, a basal dose of 100 mm of water was applied across all treatments. No rainfall was recorded throughout the entire wheat growing season. Total volume of irrigation water applied under CFI at 100%, 80%, and 60% crop water requirement was 5500, 4600, and 3700 $m^3\ ha^{-1}$, respectively. While the total volume of irrigation applied at AFI and FFI methods was 3250, 2800, and 2350 $m^3\ ha^{-1}$, respectively.

Table 2. Monthly reference evapotranspiration

Month	Minimum Temperature (℃)	Maximum Temperature (℃)	Humidity (%)	Wind (km d^{-1})	Sunshine hours (hr)	Radiation (MJ m^{-2} d^{-1})	ETo (mm d^{-1})
January	11.9	25.2	48	17	10.8	27.8	4.43
February	15.8	30.2	35	20	11.3	27.5	4.36
March	21.7	37.5	31	24	12	26.2	4.34
April	25.5	42.5	32	33	12.8	23.6	4.12
May	27.6	43.7	43	36	13.4	20.8	3.89
June	28.8	41.5	49	36	13.7	19.2	3.63
July	27.5	36.3	68	28	13.5	19.8	3.8
August	26.6	34.1	72	26	13	22.3	4.26
September	26.8	36.8	59	28	12.3	25.2	5.09
October	24.2	36.8	38	20	11.6	27.1	5.22
November	20	32.5	38	16	10.9	27.6	5.15
December	14.7	27.9	33	14	10.6	27.6	4.69
Average	22.6	35.4	46	25	12.2	24.6	4.41

Table 3. CROPWAT input for calculation of effective rainfall

Month	Rain (mm)	Effective rain (mm)
January	5	5
February	6	5.9
March	4	4
April	2	2
May	4	4
June	8	7.9
July	52	47.7
August	39	36.6
September	10	9.8
October	1	1
November	1	1
December	3	3
Total	135	127.8

Table 4. The values used as soil input in the CROPWAT model

Parameter	Values
Total available soil moisture (mm m^{-1})	210.0
Maximum rain infiltration rate (mm d^{-1})	15.0
Maximum rooting depth (cm)	120.0
Initial soil moisture depletion (%)	55%

Table 5. The crop data input in the CROPWAT model

Stages	Days	Kc
Initial	20	0.35
Crop development	30	0.75
Flowering	50	1.15
Late season	25	0.45
Total	125	

Table 6. Irrigation water requirement of the wheat crop

Month	Decade	Stage	Kc coefficient	ETc (mm d^{-1})	ETc (mm)	Effective rainfall (mm)	Irrigation required (mm)
November	3	Initial	0.35	1.27	11.4	0.5	10.9
December	1	Initial	0.35	1.2	12	0.8	11.3
December	2	Development	0.47	1.54	15.4	1.0	14.4
December	3	Development	0.74	2.63	28.9	1.2	27.7
January	1	Development	1.02	3.87	38.7	1.4	37.3
January	2	Mid	1.14	4.54	45.4	1.7	43.8
January	3	Mid	1.14	4.89	53.8	1.8	52
February	1	Mid	1.14	5.23	52.3	1.9	50.4
February	2	Mid	1.14	5.57	55.7	2.1	53.7
February	3	Late	1.11	5.82	46.5	1.8	44.7
March	1	Late	0.92	5.13	51.3	1.5	49.6
March	2	Late	0.68	4.06	40.6	1.3	36.3
March	3	Late	0.50	3.08	18.5	0.6	17.9
					470.5	17.6	450

Table 7. Total volume of water applied under all treatments

Treatments	Soaking dose (mm)	Total Irrigation amount (mm)	Total water applied (mm)	Total volume of irrigation water ($m^3 ha^{-1}$)
CFIW1	100	450	550	5500
AFIW1	100	225	325	3250
FFIW1	100	225	325	3250
CFIW2	100	360	460	4600
AFIW2	100	180	280	2800
FFIW2	100	180	280	2800
CFIW3	100	270	370	3700
AFIW3	100	135	235	2350
FFIW3	100	135	235	2350

Effect of FIMs and ILs on Crop Growth:

Plant Height:

The maximum plant height was achieved under CFI with 100% crop water requirement (64.67 ± 0.88 cm), followed by AFI (60.1 ± 1.60 cm) and FFI methods (52.67 ± 3.38 cm) (Fig. 4a). The plant height was higher under CFI, followed by AFI and FFI methods at all ILs (Fig. 4a-c). Moreover, plant height grew faster under 100% crop water requirement (Fig. 4a), followed by 80% (Fig. 4b), and 60% crop water requirement (Fig. 4c) under all FIMs. Irrigation at 100% of the crop water requirement resulted in significantly greater plant height compared to 80% and 60% irrigation levels across all FIMs. Statistical analysis indicates that plant height was significantly influenced by FIMs, ILs, and FIM × IL.

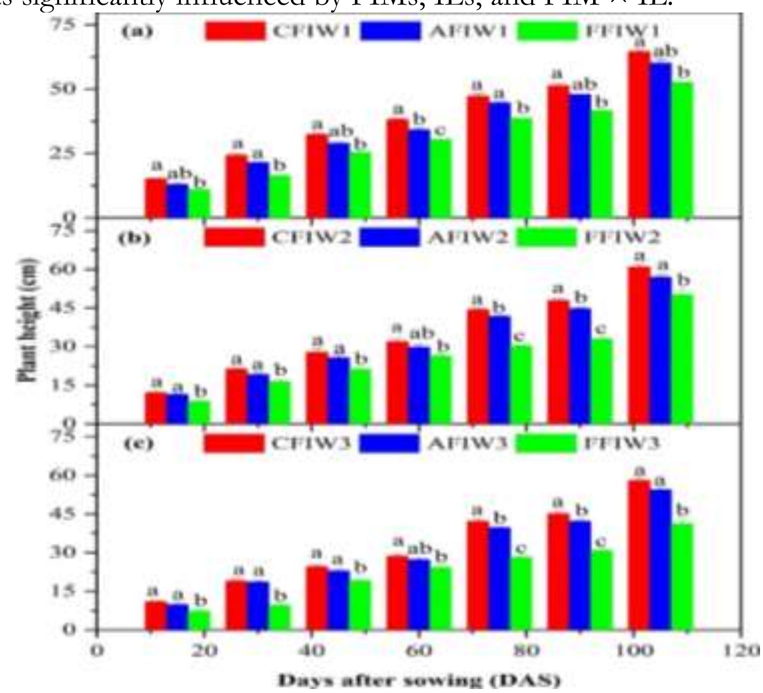

Figure 4. Plant height under different treatments at W1 (a), W2 (b), and W3 (c) irrigation levels

Note: Vertical bars indicate mean ± standard error. Different letters within each treatment indicate a significant difference among the treatments ($P < 0.05$)

Tillers:

After the first irrigation event, tiller numbers increased more rapidly under the CFI method compared to AFI and FFI at their respective ILs (Fig. 5). As the ILs increased, tiller numbers also rose across all FIMs. It was observed that CFI produced a higher number of tillers than AFI and FFI at 100%, 80%, and 60% of the crop water requirement (Fig. 5a–c).

The maximum number of tillers was measured under CFI at 100% crop water requirement of 467.75 ± 4.91 on DAS 105, and the least under FFI at 60% crop water requirement of 324.75 ± 9.14 on DAS 105. The results showed that tiller numbers increased with ILs of 100%, 80%, and 60% of the crop water requirement. Irrigating at 60% crop water requirement under all FIMs drastically lowered the tillers. Under the CFI method, irrigating at 100 of % crop water requirements produced more tillers. Statistical analysis indicates that both FIMs and ILs have a significant effect on the maximum number of tillers, while their interaction does not have a significant impact. Under all FIMs, tillers followed the trend of 100% > 80% > 60% crop water requirement.

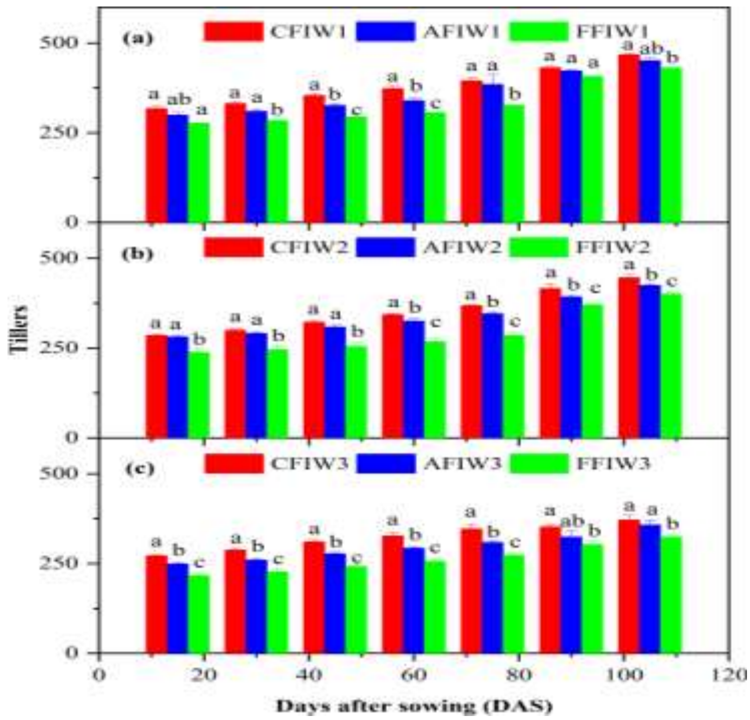

Figure 5. Tillers under different treatments at W1 (a), W2 (b), and W3 (c) irrigation levels

Note: Vertical bars indicate mean ± standard error. Different letters within each treatment indicate a significant difference among the treatments ($P < 0.05$)

Above-Ground Dry Biomass:

The above-ground dry biomass increased gradually after the first irrigation and reached peak value on DAS 105 for all treatments under all FIMs (Fig. 6). It has shown that under all FIM practices produced higher biomass at 100% crop water requirement (Fig. 6a) followed by 80% crop water requirement (Fig. 6b), and 60% crop water requirement (Fig. 6c). The maximum dry biomass was produced under CFI at 100% crop water requirement (10.32 ± 0.12 g plant^{-1}) followed by AFI (9.98 ± 0.21g plant^{-1}) and FFI (9.68 ± 0.13g plant^{-1}). While minimum dry biomass was measured under FFI (8.20 ± 0.11 g plant^{-1}), AFI (8.55 ± 0.25 g plant^{-1}), and CFI (8.95 ± 0.15 g plant^{-1}) at 60% crop water requirement. Statistical analysis illustrated that FIMs and ILs influenced notably ($P < 0.05$) above-ground dry biomass, whereas their interaction had no substantial ($P > 0.05$) effect on above-ground dry biomass.

Effects of Different FIMs and ILs on Crop Harvest:

Effective tillers (m^{-2}) varied from 382.0 ± 50.93 (FFIW3) to 597.0 ± 4.04 (CFIW1) (Table 8). The CFI method compared with the AFI and FFI methods produced 7.05%, 19.80%, and 11.13% and 33.65%, 12.41%, and 27.23% higher effective tillers at 100%, 80%, and 60% crop water requirement, respectively. The CFI method, compared with the AFI and FFI methods, produced significantly ($P < 0.05$) higher effective tillers of 9.98% and 26.46%, respectively. The 100% crop water requirement compared with 80% and 60% crop water requirements had notably higher effective tillers (m^{-2}) of 10.94% and 27.12%, respectively. The statistical examination highlighted a notable ($P < 0.01$) impact of FIMs and ILs on effective tillers (m^{-2}). The correlation between FIM and IL had no notable impact ($P > 0.01$) on effective tillers (m^{-2}).

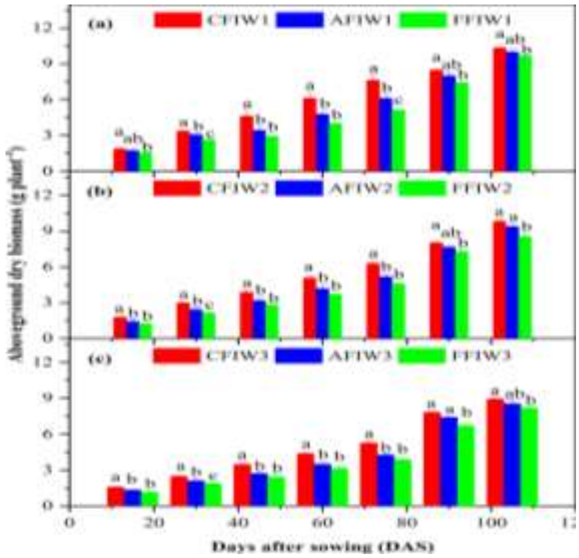

Figure 6. Above-ground dry biomass under different treatments at W1 (a), W2 (b), and W3 (c) irrigation levels

Note: Vertical bars indicate mean ± standard error. Different letters within each treatment indicate a significant difference among the treatments ($P < 0.05$)

Non-effective tillers (m^{-2}) varied from 27.0 ± 1.73 (CFIW1) to 46.0 ± 1.15 (FFIW3) (Table 8). The FFI method compared with the CFI and AFI methods produced 12.35%, 19.78%, and 18.89% and 15.89%, 12.87%, and 21.05% higher non-effective tillers at 100%, 80%, and 60% crop water requirement, respectively. The FFI method compared with the CFI and AFI methods produced significantly ($P < 0.05$) higher ineffective tillers of 14.71% and 18.91%, respectively. The 100% crop water requirement compared with 80% and 60% crop water requirements had notably higher non-effective tillers (m^{-2}) of 14.23% and 9.97%, respectively. The statistical data suggested a significant effect ($P < 0.01$) of FIMs and ILs on non-effective tillers (m^{-2}). The correlation between FIM and IL had no notable effect ($P > 0.01$) on non-effective tillers (m^{-2}).

Filled spikelets per panicle varied from 14.83 ± 0.65 (FFIW3) to 20.49 ± 0.38 (CFIW1) in all treatments (Table 8). Compared with AFI and FFI practices, CFI had significantly higher 9.20%, 22.23%, and 3.04% and 10.14%, 1.16%, and 17.75% filled spikelets per panicle at 100%, 80%, and 60% crop water requirement, respectively. Compared to AFI and FFI, CFI produced significantly higher filled spikelets per panicle, with increases of 4.59% and 16.71%, respectively. At 100% crop water requirement, compared with 80% and 60% crop water requirement, there were substantially higher 7.54% and 13.03% filled spikelets per panicle, respectively. Statistical analysis showed that FIMs and ILs substantially ($P < 0.001$) affected the filled spikelets per panicle, while their interaction had no substantial ($P > 0.05$) effect on filled spikelets per panicle.

Unfilled spikelets per panicle varied from 2.10 ± 0.10 (CFIW1) to 4.67 ± 0.33 (FFIW3) in all treatments (Table 8). Compared with CFI and AFI practices, FFI practices had 47.62%, 17.20%, and 20.0% and 25.0%, 27.71%, and 32.08% higher unfilled spikelets per panicle at 100%, 80%, and 60% crop water requirement, respectively. Compared with the CFI and AFI methods, FFI had significantly higher 63.27% and 25.08% unfilled spikelets per panicle, respectively. Additionally, the 60% crop water requirement treatment showed significantly higher unfilled spikelets per panicle 24.15% more than the 100% level and 11.15% more than the 80% level. The FIMs and ILs substantially ($P < 0.001$) affected the unfilled spikelets per panicle, while their interaction had no substantial ($P > 0.05$) effect on filled spikelets per panicle.

The CFI with a 100% crop water requirement produced a maximum spike length (8.75 ± 0.14 cm), and the FFI with a 60% crop water requirement produced a minimum spike length (6.52 ± 0.29 cm) (Table 8). The CFI compared with AFI produced 7.49%, 3.33%, and 3.61% higher spike length at 100%, 80%, and 60% crop water requirement, respectively. Compared with FFI, CFI produced 21.19%, 7.62%, and 9.97% higher spike length with 100%, 80%, and 60% crop water requirement, respectively. Additionally, relative to AFI and FFI, the CFI method resulted in significantly higher spike lengths by 4.94% and 13.11%, respectively. The 100% crop water requirement had substantially higher spike length, 11.86% and 17.04% compared with 80% and 60% crop water requirement, respectively. Statistical findings indicated that FIMs and ILs substantially ($P < 0.001$) affected the spike length, while their interaction had no substantial ($P > 0.05$) effect on spike length.

The grains per spike ranged from 19.63 ± 0.27 (CFIW1) to 15.37 ± 0.66 (FFIW3) (Table 8). The number per spike was maximum at 100% crop water requirement, moderate at 80% crop water requirement, and minimum at 60% of crop water requirement. Compared with AFI and FFI methods, the CFI method increased the grain number per spike by 10.30%, 17.80%, and 2.09% and 11.41%, 2.61%, and 10.85% at 100%, 80%, and 60% crop water requirement, respectively. Compared with the AFI and FFI methods, the CFI method increased 5.07% and 13.44% number of grains per spike, respectively. The 100% crop water requirement, compared with 80% and 60% crop water requirements had 5.05% and 10.41% higher numbers of grains per spike, respectively. The statistical results demonstrated a substantial ($P < 0.001$) impact of FIMs and ILs on the number per spike, while their interaction had no substantial ($P > 0.05$) effect on grains number per spike.

The 1000-grain weight varied from 34.0 ± 0.58 g (CFIW1) to 25.83 ± 0.38 g (FFIW3) (Table 8). The 1000-grain weight was maximum at 100% crop water requirement, moderate at 80% crop water requirement, and minimum at 60% crop water requirement under all FIMs. The CFI method compared with the AFI and FFI methods had 7.94%, 14.61%, 3.76%, and 13.13%, 6.11%, and 21.03% higher 1000-grain weight at 100%, 80%, and 60% crop water requirement, respectively. The CFI method, compared with the AFI and FFI methods had significantly higher 5.94% and 16.08% 1000-grain weight, respectively. Overall, at 100% crop water requirement compared with the 80% crop water requirement and the 60% crop water requirement had significantly higher 1000-grain weight, 3.89% and 9.93%, respectively. Analysis of the 1000-grain weight data revealed that FIMs and ILs substantially ($P < 0.001$) affected the 1000-grain weight while their interaction had no substantial ($P > 0.05$) effect on 1000-grain weight.

Grain Yield, Biomass, Water Use Efficiency, and Blue Water Footprint:

Grain Yield:

Grain yield varied from 4.57 ± 0.08 t ha^{-1} (CFIW1) to 2.15 ± 0.13 t ha^{-1} (FFIW3) (Fig. 7a). Statistical analysis depicted that FIM and IL substantially ($P < 0.001$) affected the grain yield, while their interaction had no substantial ($P > 0.05$) effect on grain yield. At ILs of 100%, 80%, and 60% of the crop water requirement, the CFI method yielded significantly more grain than the AFI method, with increases of 15.32%, 15.23%, and 11.07%, respectively. While the CFI compared with the FFI produced significantly higher 44.21%, 42.77%, and 55.50% grain yield at 100%, 80%, and 60% crop water requirement, respectively. The CFI method resulted in notably greater grain yields than the AFI and FFI methods, exceeding them by 14.04% and 46.78%, respectively. Overall, 100% crop water requirement produced 20.34% and 37.51% significantly higher grain yields compared with 80% and 60% crop water requirement, respectively.

Table 8. Effect of different furrow irrigation methods (FIM) and irrigation levels (IL) on effective tillers, non-effective tillers, filled spikelets, unfilled spikelets, spike length (cm), grains per spike, and 1000-grain weight (g)

Treatments	Effective tillers	Non-effective tillers	Filled Spikelets	Un-filled spikelets	Spike length (cm)	Grains per spike	1000-grain weight (g)
CFIW1	597.0±4.04a	27.0±1.73e	20.49±0.38a	2.10±0.1e	8.75±0.14a	19.6±0.27ac	34.0±0.58a
AFIW1	557.67±3.93ab	30.33±1.76de	18.77±0.23b	3.10±0.06cd	8.14±0.07b	17.80± 0.38b	31.50± 0.29bc
FFIW1	498.33±49.27bc	36.33±2.33c	16.77±0.68 d	3.63 ±0.19bc	7.22±0.37c	16.67±0.64bc	29.67±0.88cde
CFIW2	562.67±7.13ab	30.0±1.0de	18.10±0.12bc	2.67 ±0.03d	7.44±0.04c	17.90±0.10b	32.17±0.44b
AFIW2	506.33±3.18abc	35.67±1.2c	17.57±0.09cd	3.20± 0.06cd	7.20±0.12c	17.53± 0.09b	31.0±0.29bcd
FFIW2	421.0±43.55cd	41.33±0.88b	16.43±0.28d	4.0± 0.25b	6.91±0.10cd	16.07±0.47cd	28.43±1.06e
CFIW3	486.0±21.38bc	33.67±0.88cd	17.47±0.33cd	2.77± 0.07d	7.17±0.14c	17.03±0.23bc	31.27±0.27bcd
AFIW3	432.33± 5.36cd	38.0±0.58bc	17.27± 0.09cd	3.53± 0.24bc	6.92±0.04cd	16.60±0.17bc	29.47±0.55de
FFIW3	382.0±50.93d	46.0±1.15a	14.83±0.65 e	4.67± 0.33a	6.52±0.66d	15.37± 0.66d	25.83±0.38f
FIM	**	***	***	***	**	***	***
IL	***	***	***	**	***	***	***
FIM × IL	ns	ns	ns	ns	ns	ns	ns

Note: mean ± standard error. Different letters within each treatment indicate a significant difference among the treatments ($P < 0.05$). Significance level $^{ns}P > 0.05$, $^{***}P < 0.001$, $^{**}P < 0.01$

Biomass:

Results illustrated that FIM and IL substantially ($P < 0.05$) influenced the biomass (Fig. 7b). The maximum biomass was measured at CFIW1 (14.97 ± 0.29 t ha^{-1}) and the minimum at FFIW3 (8.97 ± 1.23 t ha^{-1}). The CFI method compared with the AFI and FFI methods had higher biomass 11.41%, 18.29%, and 12.33% and 29.34%, 4.98%, 37.17% at 100%, 80%, and 60% crop water requirement, respectively. The CFI method, compared with the AFI and FFI methods, had 9.69% and 31.20% significantly higher biomass, respectively. The biomass produced at 100% crop water requirement was substantially higher ($P < 0.05$), 10.07% and 21.48% compared with 80% and 60% crop water requirement at all FIMs, respectively.

Water Use Efficiency (WUE):

The maximum WUE was estimated 1.28 ± 0.01 kg m^{-3} under AFIW3 treatment and a minimum 0.82 ± 0.01 kg m^{-3} under CFIW2 treatment (Fig. 7c). The AFI method compared with CFI and AFI methods increased WUE by 46.75%, 42.57%, and 41.75% and 25.05%, 23.09%, and 40.0% at 100%, 80%, and 60% crop water requirement, respectively. The AFI method compared with the CFI and FFI methods yielded higher WUEs of 43.46% and 29.49%, respectively. Overall, 60% crop water requirement compared with 100% crop water requirement and 80% crop water requirement produced 2.52% and 5.37% higher WUE, respectively. Statistical analysis presented that only FIM showed a significant ($P < 0.01$) effect on WUE.

Blue Water Footprint:

Blue water footprint varied from 1216.0 ± 7.7 m^3 t^{-1} (CFIW2) to 780.8 ± 5.4 m^3 t^{-1} (AFIW3) (Fig. 7d). Compared with the CFI method, the AFI method produced significantly lower 31.74%, 29.84%, and 29.46% blue water footprint at 100%, 80%, and 60% crop water requirement, respectively. Compared with the FFI, the AFI method produced significantly lower 20.41%, 19.97%, and 29.03% blue water footprint at 100%, 80%, and 60% crop water requirements, respectively. Compared with CFI and FFI methods, AFI methods produced substantially lower 30.37% and 9.30% blue water footprint, respectively. Overall, 60% of crop water requirement produced 2.42% and 4.70% lower blue water footprint compared with 100% crop water requirement and 80% crop water requirement, respectively. Statistical analysis depicted that only FIM substantially ($P < 0.001$) affected the blue water footprint.

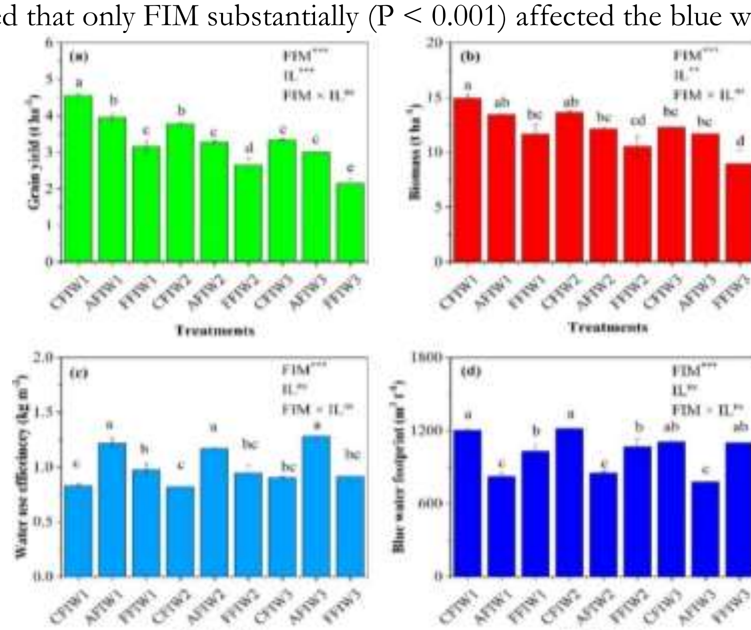

Fig 7. Effect of furrow irrigation methods and irrigation water levels on grain yield (a) biomass (b), water use efficiency (c), and blue water footprint (d)

Note: Vertical bars indicate mean ± standard error. Different letters within each treatment indicate a significant difference among the treatments (P < 0.05). Significance level ^{ns}P> 0.05, ***P< 0.001, **P < 0.01

Water saving and decrease in grain yield:

The maximum volume of water was applied under CFI and the minimum under CFI and FFI at all ILs. Under AFI and FFI applied half the amount of water was applied as CFI. The reduced irrigation water volume in AFI and FFI can be attributed to the practice of irrigating only alternate furrows and the fixed furrow, respectively, resulting in a 50% reduction in the amount of water applied. Additionally, it led to a reduction in losses from evapotranspiration and deep percolation. Compared with CFI, AFI and FFI at 100%, 80%, and 60% crop water requirement saved water 40.91%, 39.13%, and 36.49%, respectively (Fig. 8a). Compared with CFI, AFI reduced grain yield 13.28%,13.22%, and 9.97% at 100%, 80%, and 60% crop water requirement, respectively. While FFI compared with CFI decreased grain yield by 30.66%, 29.96%, and 35.69%, respectively. Overall, AFI and FFI compared with CFI saved water 39.13% and decreased grain yield 12.31% and 31.87%, respectively (Fig. 8b). While 80% and 60% crop water requirement, compared with 100% crop water requirement saved water by 15% and 30% and decreased grain yield by 16.90% and 27.28%, respectively.

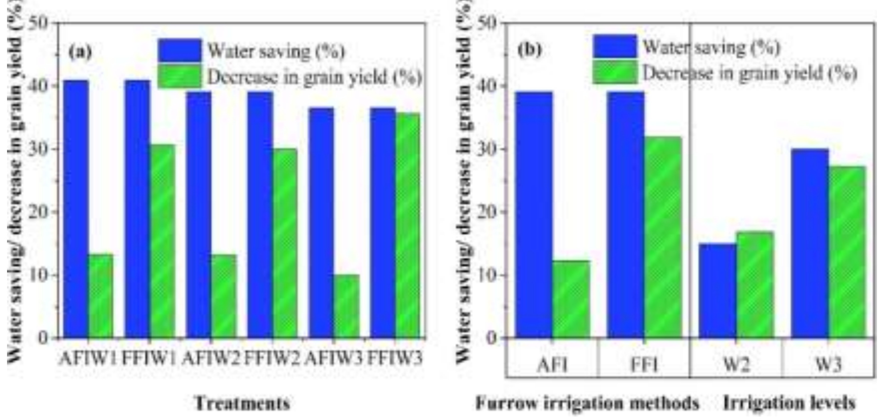

Figure 8. Decrease in grain yield (%) and water saving (%) with AFI and FFI compared with CFI **(a)** and compared with CFI and W1 irrigation level **(b)**

Discussion:

Effect of FIMs and ILs on crop growth:

Plant Height:

The results indicate that FIMs and ILs had a significant effect on plant height. Among the FIMs, CFI consistently outperforms compared with AFI and FFI methods in promoting taller crop plants. This can be attributed to CFI efficiency in water distribution, and uniform moisture levels contribute to healthier and vigorous plant growth. In contrast, AFI and FFI with variable water distribution and limited water reach show reduced effectiveness in promoting plant height [44]. In this study, CFI consistently led to taller crop plants compared with AFI and FFI methods, which agrees with the findings of authors [45] [46], who also reported that the CFI method leads to the highest plant height, followed by AFI and FFI. Water availability directly affects plant height, with higher levels promoting taller growth and lower levels reducing it. Water availability directly influenced plant height, with IL increasing from 60% to 80% to 100% of crop water requirement, producing progressively higher plant height. This highlights the importance of adequate water availability in promoting robust plant growth, as plants with higher water levels exhibited less moisture stress, leading to taller crops. Similar observations were reported by author [47], who found that certain wheat cultivars exhibited improved growth under different ILs. Results illustrated that a sufficient level of moisture is crucial for the proper growth and development of crops. These findings align with author's [48] study, which demonstrated that a lack of water during the tillering growth stage led to a decrease in the number of fertile tillers, ultimately resulting in reduced wheat crop height.

Tillers:

Results revealed that CFI significantly increases the tillers compared with AFI and FFI across all ILs. The tillers increased substantially from 60% to 80% to 100 of % crop water requirements. These findings are also consistent with author [47] that the maximum number of tillers was recorded in higher irrigation levels (362.22) and the minimum in the least irrigation treatment (278.44). The maximum number of tillers in higher irrigation may be due to adequate availability of water, ensuring more uptake of nutrients. This emphasizes the importance of water level in wheat cultivars and FIMs in influencing tiller development. Further, it provides valuable insights into optimizing irrigation strategies for wheat cultivation to maximize tiller formation and improve crop yield.

Above-Ground Biomass:

In wheat cultivation, above-ground biomass is a crucial indicator for estimating grain yield and WUE. Results showed that above-ground dry biomass in wheat crops increased gradually after 15 DAS and reached its peak value on DAS 105 under different FIMs and ILs. The maximum biomass was produced by CFI, followed by AFI and FFI at 100% crop water requirement. The study found that reduced water application (60% and 80% crop water requirement) decreased biomass production in wheat crops, while well-watered conditions (100% crop water requirement) enhanced biomass. The above-ground dry biomass yields increased, which can be attributed to taller plant height, more tillers, and better seed growth [49]. This finding aligns with author [50] study emphasizing the importance of improving biomass production for achieving greater yield in water-scarce regions where wheat biomass at maturity tends to decrease significantly under low water regimes. Similarly, author [51] found that above-ground biomass was significantly changed under all deficit irrigation treatments, observed the highest mean above-ground biomass of 11,397 kg ha^{-1} during 2018-2019, followed by 11,170 kg ha^{-1} in the control treatment during 2017-2018. The study emphasizes the importance of effective irrigation management in maximizing above-ground biomass production.

Effect of FIMs and ILs on Yield Attributes:

Effective and Non-Effective Tillers:

The study found that the choice of FIM and IL significantly affects the production of effective tillers in wheat crops. However, the number of non-effective tillers did not show a substantial difference across different FIMs and ILs. This is consistent with previous research showing an increase in effective tiller numbers with higher irrigation frequency [52]. Low ILs led to water stress in plants, while higher ILs delayed tiller production, delaying maturity and potentially hindering nutrient competition, ultimately resulting in reduced grain filling [53].

Filled and unfilled spikelets:

The filled spikelets per panicle in wheat crops significantly vary across different FIMs and ILs. The CFI at 100% crop water requirement had the highest number of filled spikelets per panicle (20.49 ± 0.38). FFI at 60% crop water requirement had the lowest number of filled spikelets per panicle (14.83 ± 0.65). Unfilled spikelets also varied significantly, with the maximum number of unfilled spikelets per panicle observed under FFI at 60% crop water requirement (4.67 ± 0.33), and the minimum number of unfilled spikelets was recorded under CFI at 100% crop water requirement (2.1 ± 0.10). The study suggests that the choice of FIM and IL can significantly impact spikelet development, potentially leading to improved grain yield and quality.

Spike Length and Grains Per Spike:

In this study, CFI at 100% crop water requirement produced the longest spikes (8.75 ± 0.14 cm), and the FFI at 60% crop water requirement produced the shortest spike length (6.52 ± 0.66 cm). The maximum grains per spike were recorded under CFI at 100% crop water requirement (19.63 ± 0.27), and the minimum grains per spike were measured under FFI at 60% crop water requirement (15.37 ± 0.66). The highest grain count was observed at 100% crop water requirement, followed by 80% and 60% crop water requirement. Similarly, author [54] suggested that both the choice of irrigation methods and IL significantly influence spike length and grains per spike in wheat crops. The grains per spike are particularly sensitive to water shortage, making it so that wheat crops cannot endure a lack of water from the early stages of growth to maturity. Water stress, particularly during the anthesis or tillering stage, can significantly reduce spike length and grains, ultimately affecting flowering and grain-filling stages [55][56].

1000-grain weight:

In this study, CFI at 100% crop water requirement yielded the highest 1000-grain weight (34.0 ± 0.58 g), and the lowest was in the FFI at 60% crop water requirement (25.83 ± 0.38 g). These results agreed with author [57] measured 1000-grain weight ranging from 42.6 to 43.8g in different treatments, possibly due to improved climatic conditions and increased irrigation water usage. Additionally, 1000-grain weight increased with increasing irrigation frequency. Author [58] reported that plants with limited water supply produced lighter grains due to reduced nutrient availability. The study underscores the significance of proper irrigation management in affecting 1000-grain weight, with higher levels resulting in heavier grains.

Effect of FIMs and ILs on grain yield and biomass:

Grain yield:

The CFI achieved better yield over the AFI and FFI methods at all ILs. The CFI with 100% crop water requirement produced the highest yield of 4.57 t ha$^{-1,}$ while the AFI and FFI with double the amount of water application produced 3.96 t ha^{-1} and 3.17 t ha^{-1} total yield, respectively. Overall, AFI produced a grain yield of 3.42 t ha^{-1} while the CFI (double the amount of water) and FFI system gave 3.9 t ha^{-1} and 2.66 t ha^{-1} grain yield, respectively. Whereas 80% crop water requirement produced 16.92% lower yield, with 15% of the water saved compared with 100% crop water requirement.

The results revealed that growth performance under different FIMs with ILs; as the amount of water application decreased from 100% to 80% to 60% crop water requirement, the yield reduction also increased. The yield reduced from 9.97-13.28% and 29.96-35.69% under AFI and FFI, respectively, compared with CFI at different ILs. Moreover, 80% and 60% crop water requirement decreased grain yield 16.92% and 27.44% compared with 100% crop water requirement, respectively. These results showed better results lie under AFI with 100% and 80% crop water requirement, and FFI at 100% of crop water requirement.

The AFI has proven to be a successful technique for conserving water in irrigation [59]. Results showed that AFI reduced irrigation water use by 39.13% and reduced yield by 13.22% compared with CFI. These results align with earlier findings of authors [60] [61] [62] [63]. The result shows that ILs have a significant effect on grain yield. Wheat yields are negatively impacted by water shortages; however, grain yields can be raised by increasing irrigation [64]. In this study, grain yields were lowest in the 60% crop water requirement treatments and tended to increase with increasing IL, in agreement consistent with authors [65] [66].

Overall, AFI decreased grain yield by 12.31% and FFI by 31.79% compared with CFI, while reducing water application by nearly 40% in the case of AFI. This suggests that switching from CFI to water-saving AFI and FFI irrigation techniques might potentially double the amount of arable land and productivity while utilizing the current irrigation water resource.

Implementing water-saving irrigation techniques also contributes to reducing the negative environmental effects of excessive irrigation and community disputes over scarce water resources.

CFI is demanding in terms of labor and time, requiring irrigation for each furrow at every frequency. In contrast, AFI necessitates half the labor, time, and irrigation quantity. Conversely, in regions facing water scarcity and high labor costs, the AFI system emerges as the optimal choice for boosting wheat production. Thus, in areas with limited water resources for irrigation, particularly in arid, semi-arid, or climatically similar regions, the AFI method allows for the utilization of 80% of the crop water requirement, resulting in a marginal 13.28% yield reduction and significant water savings.

Biomass:

The study showed that biomass production was higher when irrigation was maintained at 100% of crop water requirement, compared with 80% and 60% of crop water requirement. Both FILs and ILs significantly influenced biomass. Maximum biomass was observed in CFI, followed by AFI and FFI at all ILs. Moreover, biomass was substantially higher at 100% crop water requirement compared with 80% and 60% crop water requirement. The increased above-ground biomass in CFI at 100% crop water requirement wheat plants due to taller plants, a higher number of tillers, and improved grain growth [49]. These findings are consistent with author [50] study reported that in semi-arid conditions, producing higher wheat biomass is necessary for higher yield, as biomass at maturity significantly reduced from high to low water levels. Similarly, author [67] observed that grain yield improved under adequate water conditions and biomass reduced under reduced water applications.

Effect of FIMs and ILs on WUE:

The highest WUE was achieved in the AFI, moderate in the FFI, and lowest in the CFI at all ILs. The CFI resulted in lower WUE across all ILs, showing a substantial yield with higher consumption of water. Moreover, it also results in substantial loss of water due to deep percolation and evapotranspiration. Decreasing the water demand of wheat by 60% provided the WUE 1.28 kg $m^{-3,}$ followed by a 100% wheat water requirement of 1.22 kg m^{-3}. Regardless of the highest WUE with 50% less irrigation water consumed at FFI and AFI, the yield penalty was significant, 14.04% and 46.78% respectively, compared with CFI, respectively. The results indicate that the combined effect of FIM and ILs saves a significant amount of water. Hence, it could increase additional irrigable land and/or improve or minimize operation or variable cost. The AFI technique demonstrated water-saving capabilities by reducing the wetted surface area, resulting in decreased evapotranspiration and deep percolation. Compared with the CFI method, AFI and FFI exhibited water savings of approximately 39.13%. Water saved from treatment, combined with AFI and FFI, with 100%, 80%, and 60% crop water requirement, were 40.91%, 39.13%, and 36.49% of the total volume applied compared with CFI, respectively.

These results are in line with author's [68] study, which indicated a 27% increase in stover yield and a 17% increase in grain yield for maize with AFI compared with CFI. It also concurs with author [69] findings, that 35% improvement in WUE for potato with AFI compared with CFI, while maintaining grain yield. Author [70] also documented the highest WUE of 5.29 kg m^{-3} using AFI, in contrast to the 2.78 kg m^{-3} achieved with CFI in okra production. The maximum WUE using the AFI method was also documented for maize [59] and tomato [31] crops. These findings align with the reported water savings of 28–35% for potato [69][71], 37–39% tomato [31], 50% Okra [70], and 37% maize [72] crop production with AFI compared with CFI. Moreover, Authors [73] [71] noted a 46–50% reduction in irrigation water usage with the implementation of AFI compared to CFI. These findings reinforce the present study's conclusion that AFI is a robust and scalable irrigation approach for arid and semi-arid wheat production, capable of improving WUE and conserving water without severely compromising yield.

Effect of FIMs and ILs on the blue water footprint:

At all ILs, AFI resulted in significantly lower blue water footprint values (780.73 to 852.79 m^3 t^{-1}) compared with CFI and FFI. On the contrary, CFI consistently recorded the highest values for blue water footprint (ranging from 1106.68 to 1215.86 m^3 t^{-1}), highlighting it as the least effective FIM for blue water footprint. At all ILs, FFI performed better than CFI, and had a significantly lower blue water footprint compared with CFI. This convergence in performance under a 60% crop water requirement might indicate that under reduced water conditions, the differences among FIMs become less pronounced, possibly due to an overall stress effect that limits potential. The superior performance of AFI in minimizing blue water footprint is likely due to better water distribution and retention, enabling more efficient use of irrigation water. The results further indicated that among different FIMs, AFI with an 80% crop water requirement can ensure yield and water saving, which is the most appropriate irrigation practice. The IL has no substantial influence on the blue water footprint but shows an obvious difference under different FIMs.

These results are consistent with author [74] observations that applying 80% of the net irrigation requirement to barley in Spain minimized water footprint. Similarly, authors [75] examined how different management practices influenced the water footprint of winter wheat at the Xiaotangshan Station in Beijing. They observed that transitioning from full to deficit irrigation resulted in a 38% decrease with only 9% yield reduction. The implications for our study site are clear: adopting AFI with 80% crop water requirement can effectively reduce blue water footprint without compromising productivity, even under semi-arid conditions. Combining water-saving infrastructure with precise irrigation scheduling and technology selection, tailored to local production conditions, can ensure that water footprint improvements are both achievable and sustainable under conditions of water scarcity.

Conclusions:

The results illustrated that furrow irrigation methods and irrigation levels significantly influenced crop growth (plant height, tillers, and aboveground dry biomass), yield attributes (effective and non-effective tillers, filled and unfilled spikelets per panicle, spike length, grains per spike, and 1000-grain weight), grain yield, biomass, WUE, and blue water footprint of wheat crop. The CFI compared with AFI improved crop growth, produced higher grain yield (11.1-15.3%), biomass (5.0-12.3%), lower WUE (29.45-31.86%), higher blue water footprint (41.7-46.7%), and higher volume of water (57.45-69.23%) at different irrigation levels. Whereas irrigating with AFI saved irrigation water (36.49-40.91%), higher WUE (41.75-46.75%), lower yield (9.97-13.28%), and lower blue water footprint (29.45-31.86%) compared with CFI at different irrigation levels. Moreover, AFI compared with CFI at 80% crop water requirement saved water 39.13%, improved WUE 29.86%, lowered blue water footprint 29.86%, and decreased wheat yield by 13.22%. In semiarid regions, adoption of AFI coupled with an 80% reduction in water requirements, not only conserved irrigation water but also enhanced WUE without significantly compromising grain yield. The implementation of the AFI technique highlights the significant potential to double cultivable land and production using existing irrigation water resources by transitioning from the CFI to the water-saving AFI method. It is recommended that using an AFI method combined with 80% of the wheat crop water requirement is the optimal choice to boost wheat production, higher WUE, and lower blue water footprint in regions facing water scarcity. For future research directions, experiments should be conducted incorporating thorough soil moisture monitoring and the AFI method to further enhance wheat yield and WUE.

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