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Effects of Water Deficit at Different Growth Stages on Maize Growth & Yield under Alternate Partial Root-Zone Irrigation

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ABSTRACT

Water scarcity is an increasing constraint on maize production in semi-arid environments, where the timing and intensity of soil-water deficit can determine whether a crop maintains yield or experiences major reproductive losses. Alternate partial root-zone irrigation (APRI) is designed to keep part of the root system hydraulically active while the opposite portion dries, thereby combining water saving with physiological regulation of transpiration. This paper presents a revised analysis of a maize experiment conducted at the International Water Management Institute, Rahim Yar Khan, Pakistan, during the 2022–2023 growing season. The reported experiment used a factorial arrangement of three irrigation levels—100%, 60%, and 40% field capacity—with three replications and evaluated plant height, leaf number, leaf relative water content (LRWC), SPAD chlorophyll index, shoot biomass, root biomass, biological yield, grain yield, and harvest index. Across the available aggregate data, declining water availability reduced vegetative growth, leaf hydration, chlorophyll status, total biomass, and grain yield. Plant height fell from 198.4 cm at 100% field capacity to 149.3 cm at 40% field capacity, while grain yield declined from 7.62 to 4.93 t ha−1. Moderate deficit irrigation retained 89.4% of the full-irrigation grain yield and produced the highest reported harvest index (44.2%). Root biomass was also greatest at 60% field capacity, suggesting a possible shift toward below-ground allocation under moderate stress. Because the supplied manuscript does not include raw observations, genotype-by-irrigation means, stage-specific means, irrigation volumes, or a numerical water-use-efficiency calculation, the present revision limits quantitative conclusions to the four reported aggregate tables. The results support moderate APRI as a promising water-saving strategy, but they also demonstrate the need for complete treatment-level data and replicated field validation before making genotype-specific recommendations.

Introduction

Pakistan is an agriculture-based economy comprises many of its subsidiaries including animal, crops, horticulture, pomology, forestry, and fruit sectors (Jabeen et al., 2023). Maize (*Zea mays* L.) is a cereal plant that produces a lot and is important for food, animal feed, making products, and helping rural communities in various farming areas. However, its ability to grow well relies on having enough water during key stages such as when the leaves are forming, during flowering, and while the grains are developing. When there is not enough water, it negatively affects how cells grow, how leaves expand, how the plant takes in carbon from the air, how nutrients move within the plant, and how the nutrients get to the growing kernels (Hsiao, 1973; Farooq et al., 2009; Lawlor and Cornic, 2002). The overall outcome is not consistent: a small to medium lack of water might be somewhat reversible if more water is provided later, while extreme or poorly timed drought can lead to lasting harm to breeding success (Herrero and Johnson, 1981; Lobell et al., 2014). The issue is particularly significant in farming areas that have dry and semi-dry conditions. There is growing competition for water used for irrigation between farming, industry, home use, and the environment (FAO, 2017). Meanwhile, high rates of evaporation and unpredictable rainfall make it more likely that corn will face water shortages at critical times. Traditional irrigation methods, especially when applied evenly throughout the root area, can support plant development but may also elevate evaporation rates, lead to deeper water loss, increase runoff, and result in the loss of nutrients. Consequently, how we manage irrigation needs to be assessed not only by how much is harvested but also by how much water is needed and when it is needed to achieve that harvest (Fereres and Soriano, 2007; Kang and Zhang, 2004; Kang et al., 2000).

Alternate partial root-zone irrigation is a type of controlled deficit watering in which just a section of the root area is moistened at a specific moment, and the side that receives water is switched out from time to time (Li et al., 2007; Davies and Zhang, 1991). The approach relies on how water is absorbed and the chemical signals sent from roots to shoots. Roots in parched soil might boost the signaling of abscisic acid, leading to a limited opening of stomata and less water loss through transpiration, whereas the side with irrigation continues to deliver water to the upper part of the plant. This process does not ensure that yields will be maintained in every setting; its success relies on factors such as soil type, depth of roots, weather demand, how often irrigation occurs, how packed the crops are, and the intensity and timing of water shortage (Hsiao, 1973; Farooq et al., 2009).

Therefore the present study was conducted to elucidate the impact of decreased soil-water have on maize development, plant water condition, biomass distribution, and production.

Materials and Methods

Experimental site and season

The experiment was conducted at the International Water Management Institute (IWMI), Rahim Yar Khan (28.4200° N and 70.3035° E), Pakistan, during the 2022–2023 growing season. Rahim Yar Khan represents a hot, semi-arid production environment in which irrigation scheduling is central to crop establishment and yield stability. The supplied research does not report a complete soil profile, weather series, plot dimensions, planting date, cultivar descriptors, fertilizer rates, or measured irrigation volumes. These omissions are recorded as reporting limitations rather than filled with assumptions.

Experimental design and irrigation treatments

The research describes a completely randomized factorial arrangement with three replications. The factors were maize genotype and irrigation treatment, although the genotype-level results are not numerically available in the supplied document. The quantitative comparison used in this paper consists of three reported soil-water targets: 100% field capacity (control), 60% field capacity (moderate deficit), and 40% field capacity (severe deficit). APRI was described as alternating irrigation between opposite portions of the root system so that one side was wetted while the other side was allowed to dry before alternation.

Table 1. Operational interpretation of the irrigation levels reported in the supplied manuscript.

Treatment code	Target soil-water level	Interpretation
I100	100% FC	Full irrigation / control
I60	60% FC	Moderate water deficit
I40	40% FC	Severe water deficit

Measured variables

The reported measurements comprised plant height, number of leaves, LRWC, SPAD chlorophyll index, shoot biomass, root biomass, biological yield, grain yield, and harvest index.

Data handling and derived indicators

The four source tables were transcribed without altering their reported means or significance letters. Two additional analytical quantities were derived from those means. First, the percentage change from 100% to 40% field capacity was calculated as

$$[(value\ at\ 40\%\ FC\ -\ value\ at\ 100\%\ FC)\ /\ value\ at\ 100\%\ FC]\ \times\ 100$$

Second, the root-to-shoot biomass ratio was calculated as root biomass divided by shoot biomass. These calculations are descriptive and do not create new experimental observations.

Table 2. Derived indicators calculated from the reported aggregate means.

Indicator	Formula used	Purpose
Extreme-stress change (%)	(I40 − I100) / I100 × 100	Describe the full-irrigation to severe-deficit shift
Root: shoot ratio	Root biomass / shoot biomass	Describe relative biomass allocation
Yield retention at I60 (%)	I60 grain yield / I100 grain yield × 100	Assess moderate-deficit yield preservation

Field Measurements

Plant Height and Number of Leaves

The plant height(cm) and the number of leaves per plant were recorded on the sampled plants of each replication, and the mean value of each treatment was calculated using Equations (1) and (2):

$$PH_{mean} = (\Sigma_{i=1}^{m} H_i) / m \quad (1)$$

$$NL_{mean} = (\Sigma_{i=1}^{m} N_i) / m \quad (2)$$

where PH_{mean} is the mean plant height (cm); NL_{mean} is the mean number of leaves per plant; H_i is the height (cm) of the ith plant; N_i is the number of leaves on the ith plant; and m is the number of plants measured.

Leaf Relative Water Content (LRWC)

LRWC was used as a measure of leaf hydration and was calculated from the fresh weight, turgid weight, and dry weight of the leaf samples using Equation (3):

$$LRWC = [(FW - DW) / (TW - DW)] \times 100 \quad (3)$$

where LRWC is the leaf relative water content (%); FW is the fresh weight of the leaf sample (g); TW is the turgid weight of the leaf sample after rehydration (g); and DW is the dry weight of the leaf sample (g).

SPAD Chlorophyll Index

The SPAD value was recorded with a chlorophyll meter and is treated as a relative chlorophyll index rather than a direct laboratory concentration of chlorophyll. The SPAD value of each treatment was calculated as the mean of the readings taken, using Equation (4):

$$SPAD_{mean} = (\Sigma_{j=1}^{n} S_j) / n \quad (4)$$

where $SPAD_{mean}$ is the mean SPAD value; S_j is the jth SPAD reading; and n is the number of readings.

Shoot Biomass, Root Biomass, and Root-to-Shoot Ratio

Shoot biomass and root biomass were expressed on a per-plant basis (g plant^{-1}) and were calculated using Equations (5) and (6). The root-to-shoot biomass ratio, used to describe relative biomass allocation, was calculated using Equation (7):

$$SB = W_s / N_s \quad (5)$$

$$RB = W_r / N_r \quad (6)$$

$$R{:}S = RB / SB \quad (7)$$

where SB is the shoot biomass (g plant^{-1}); RB is the root biomass (g plant^{-1}); W_s and W_r are the total shoot and root weights of the sampled plants (g); N_s and N_r are the numbers of plants sampled for shoot and root biomass; and $R{:}S$ is the root-to-shoot biomass ratio (dimensionless).

Biological Yield, Grain Yield, and Harvest Index

Biological yield refers to the total above-ground dry matter at harvest. Biological yield and grain yield were calculated on a per hectare basis (t ha^{-1}) using Equations (8) and (9), and the harvest index was calculated as the grain-yield fraction of biological yield, expressed as a percentage, using Equation (10):

$$BY = (W_b / A) \times 10 \quad (8)$$

$$GY = (W_g / A) \times 10 \quad (9)$$

$$HI = (GY / BY) \times 100 \quad (10)$$

where BY is the biological yield (t ha^{-1}); GY is the grain yield (t ha^{-1}); HI is the harvest index (%); W_b and W_g are the above-ground dry matter weight and the grain weight of the harvested area (kg); A is the harvested area (m^2); and 10 is the factor converting kg m^{-2} to t ha^{-1}.

Statistical Analysis

The data were analyzed by analysis of variance, and treatment means were separated using the least significant difference (LSD) test at the 5% probability level (Steel et al., 1997).

Results

Effects of Different Irrigation Levels on Morphological Parameters

The reported aggregate means showed a consistent decline in vegetative growth as the irrigation target decreased. Plant height was 198.4 cm under 100% field capacity, 176.9 cm under 60% field capacity, and 149.3 cm under 40% field capacity (Figure 1a). Relative to the fully irrigated treatment, moderate deficit reduced plant height by 10.8%, whereas severe deficit reduced it by 24.7%. The number of leaves followed the same direction, declining from 14.2 to 12.6 and 10.9 leaves per plant, respectively (Figure 1b).

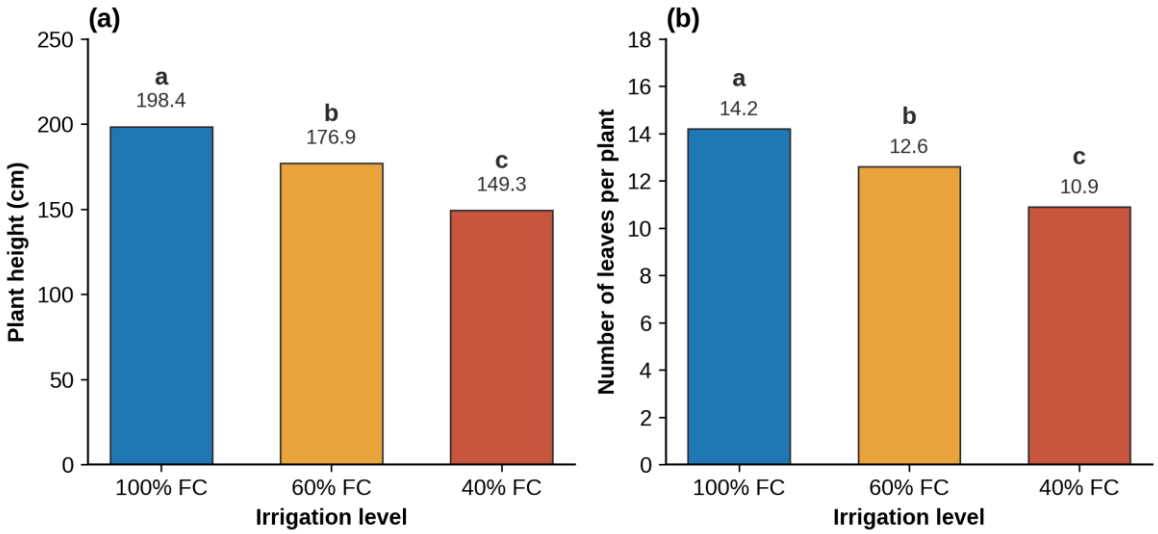


Figure 1. Plant height and number of leaves under the reported irrigation levels.

(a) Plant height decreased progressively as the reported soil-water target declined. (b) The number of leaves followed the same direction. Column chart. Different letters indicate differences reported as significant at $p \leq 0.05$.

Shoot biomass was highest under full irrigation at 312.5 g plant^{-1} and declined to 276.4 g plant^{-1} at 60% field capacity and 214.8 g plant^{-1} at 40% field capacity (Figure 2). The severe treatment therefore reduced shoot biomass by 31.3% relative to the control. Root biomass showed a different response: it increased from 78.2 g plant^{-1} under full irrigation to 86.7 g plant^{-1} under moderate deficit, then declined to 61.9 g plant^{-1} under severe deficit. This non-linear response is important because it indicates that moderate stress may have encouraged relative investment in roots, while severe stress constrained both shoot and root production.

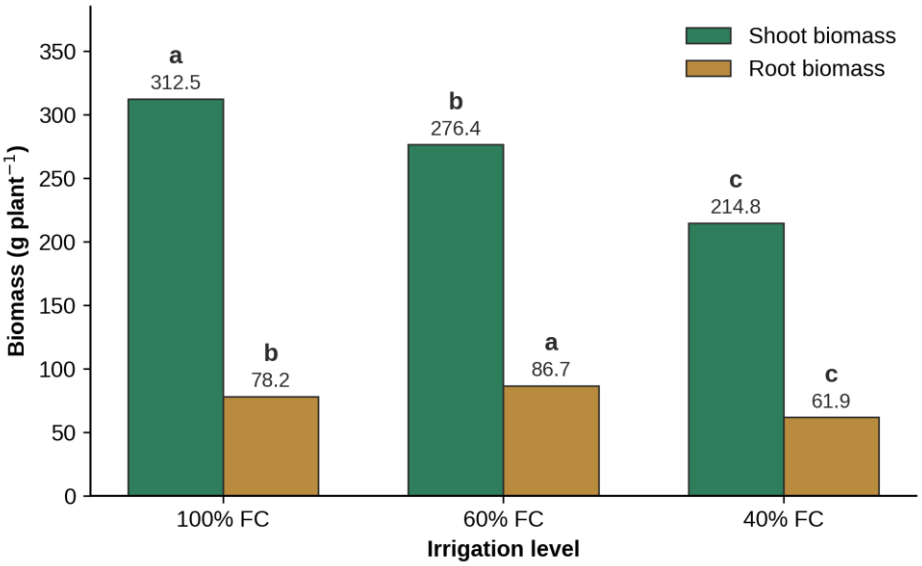


Figure 2. Shoot and root biomass responded differently to irrigation level.

Moderate deficit had the highest reported root biomass, whereas severe deficit reduced both biomass components. Grouped column chart. Different letters indicate differences reported as significant at $p \leq 0.05$.

The root-to-shoot ratio increased from 0.250 under full irrigation to 0.314 under moderate deficit, an increase of 25.6%, before falling to 0.288 under severe deficit (Figure 3). This ratio should not be interpreted as proof of deeper rooting because root length, root volume, and soil-profile distribution were not measured. It does, however, provide a useful descriptive signal that moderate stress altered biomass partitioning.

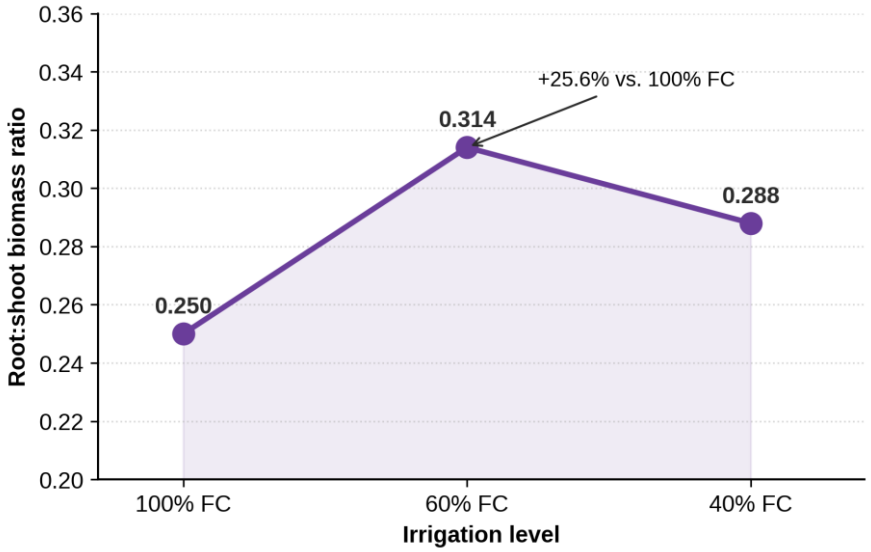


Figure 3. Root-to-shoot biomass ratio (root biomass / shoot biomass) calculated from the reported means. Line chart with area fill.

Effects of Different Irrigation Levels on Physiological Parameters

Leaf relative water content decreased from 84.6% at 100% field capacity to 76.8% at 60% field capacity and 65.4% at 40% field capacity (Figure 4a). The 40% treatment was therefore associated with a 22.7% lower LRWC than the control. SPAD value also declined from 52.3 to 46.1 and 38.7, corresponding to a 26.0% reduction between 100% and 40% field capacity (Figure 4b). The parallel declines in LRWC and SPAD are consistent with progressive loss of leaf hydration and chlorophyll-related photosynthetic capacity as water limitation intensified. The moderate treatment retained 90.8% of control LRWC and 88.1% of control SPAD value. This pattern suggests that 60% field capacity imposed measurable stress without producing the severe physiological deterioration observed at 40% field capacity. Because gas exchange, fluorescence, pigment extraction, and leaf temperature were not reported, the present interpretation remains indicative rather than mechanistic.

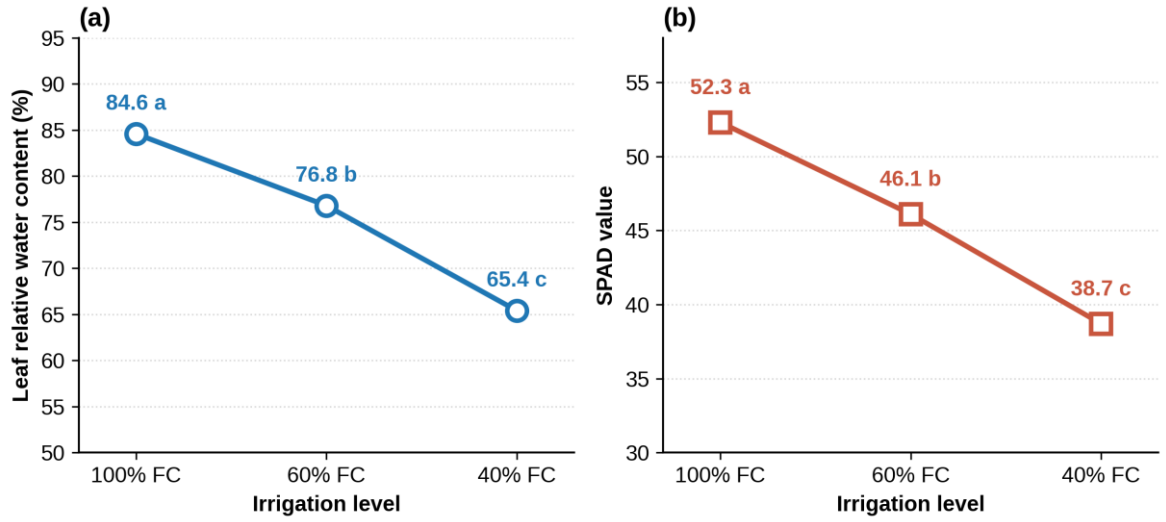


Figure 4. Leaf relative water content (a) and SPAD value (b) declined under progressively stronger water deficit. Line chart. Different letters indicate differences reported as significant at p ≤ 0.05.

Effects of Different Irrigation Levels on Grain Yield and Harvest Index

Grain yield was 7.62 t ha^{-1} under full irrigation, 6.81 t ha^{-1} under moderate deficit, and 4.93 t ha^{-1} under severe deficit (Figure 5a). Moderate deficit retained 89.4% of the control grain yield, whereas severe deficit retained 64.7%. Biological yield declined from 17.8 to 15.4 and 12.1 t ha^{-1}. Harvest index was highest under moderate deficit at 44.2%, compared with 42.8% under full irrigation and 40.7% under severe deficit (Figure 5b). The combination of relatively high yield retention and the highest harvest index makes 60% field capacity the most balanced treatment in the supplied aggregate data, although it did not maximize absolute grain yield.

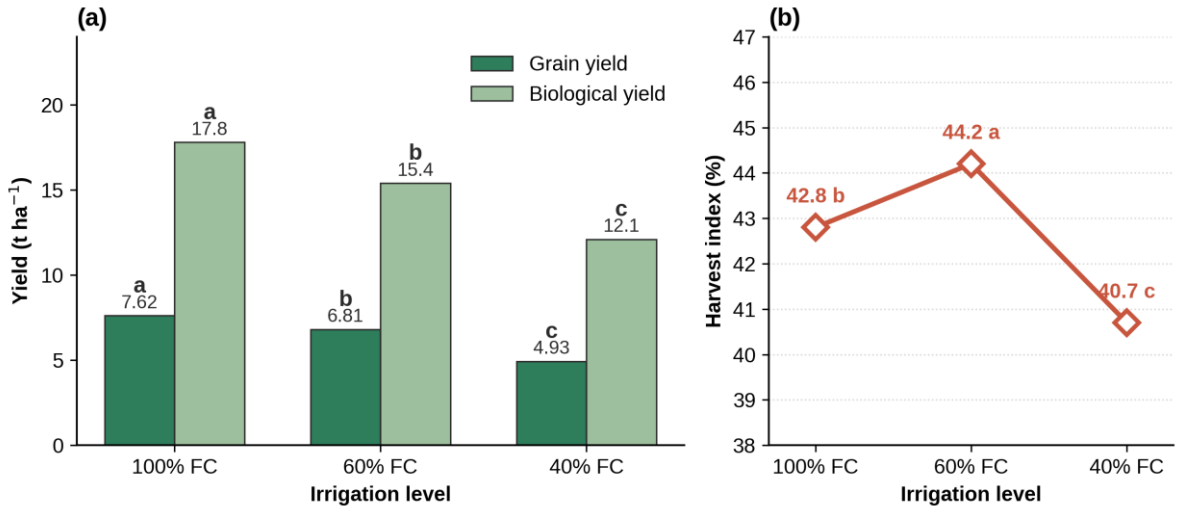


Figure 5. Yield and harvest index response to irrigation level. (a) Grain yield and biological yield (column chart); (b) harvest index (line chart). Different letters indicate differences reported as significant at p ≤ 0.05.

Integrated Response across Indicators

The irrigation treatments produced a coherent severity gradient (Table 3, Figure 6). The control maximized plant height, leaf number, LRWC, SPAD value, shoot biomass, biological yield, and grain yield. Moderate deficit reduced most absolute growth variables but increased root biomass and harvest index. Severe deficit reduced every measured indicator, and none of the measured traits showed compensation. This pattern is consistent with a threshold response: moderate deficit may trigger acclimation and altered allocation, while severe deficit exceeds the plant's ability to maintain both vegetative and reproductive functions.

Table 3. Consolidated response matrix and calculated change from full irrigation to severe deficit. Different letters indicate differences reported as significant at p ≤ 0.05. The root:shoot ratio is a derived value and carries no letters.

Indicator	100% FC	60% FC	40% FC	Change: 100%→40%
Plant height (cm)	198.4 a	176.9 b	149.3 c	−24.7%
Number of leaves	14.2 a	12.6 b	10.9 c	−23.2%
LRWC (%)	84.6 a	76.8 b	65.4 c	−22.7%
SPAD value	52.3 a	46.1 b	38.7 c	−26.0%
Shoot biomass (g plant^{-1})	312.5 a	276.4 b	214.8 c	−31.3%
Root biomass (g plant^{-1})	78.2 b	86.7 a	61.9 c	−20.8%
Grain yield (t ha^{-1})	7.62 a	6.81 b	4.93 c	−35.3%
Biological yield (t ha^{-1})	17.8 a	15.4 b	12.1 c	−32.0%
Harvest index (%)	42.8 b	44.2 a	40.7 c	−4.9%
Root:shoot biomass ratio	0.250	0.314	0.288	+15.2%

The strongest relative decline among the reported traits was observed for grain yield (35.3%), followed by biological yield (32.0%), shoot biomass (31.3%), SPAD value (26.0%), plant height (24.7%), number of leaves (23.2%), LRWC (22.7%), and root biomass (20.8%), as calculated from the means (Table 3). These comparisons are descriptive and should not be mistaken for effect sizes with confidence intervals because the replication-level variance was not available.

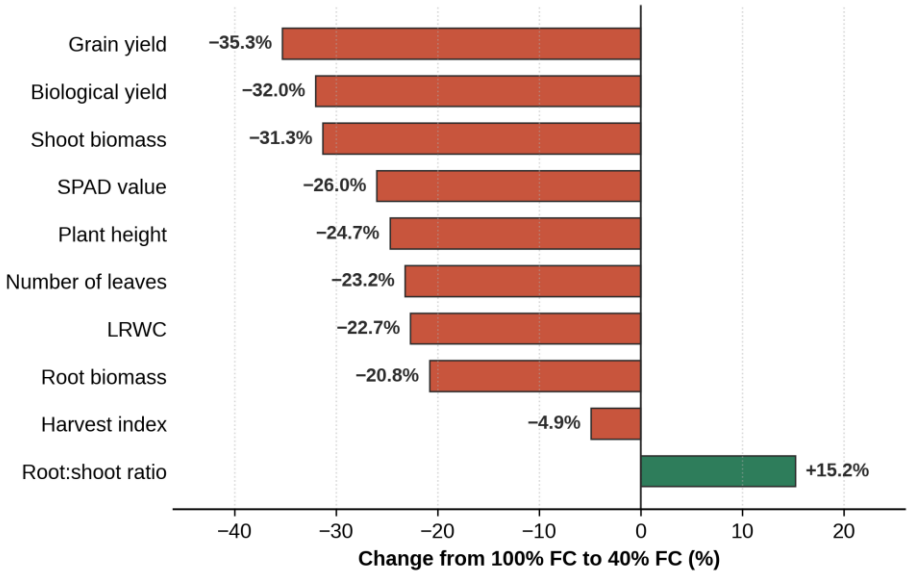


Figure 6. Calculated change in each reported indicator from 100% FC to 40% FC. Horizontal bar chart derived from the reported means.

Discussion

Water scarcity limits the growth of maize by preventing cell enlargement, reducing how well the stomata work, and decreasing the plant's ability to use carbon during photosynthesis (Hsiao, 1973; Farooq et al., 2009; Lawlor and Cornic, 2002), and the overall impact relies heavily on how serious and when the stress occurs (Herrero and Johnson, 1981). In this study, it was observed that as field capacity (FC) dropped from 100% to 60% and then to 40%, the height of the plants decreased by 10.8% and 24.7%, and the number of leaves went down from 14.2 to 10.9 per plant. This proves the results by (Avramova et al., 2015), who highlighted that drought affects growth in the maize leaf growth area, and (Zhou et al., 2020) explain how stress from lack

of water alters the traits of maize leaves. (Huang et al., 2022) found that in summer maize, a single irrigation reduced plant height by 19.9% and leaf area index by 30.3% compared to full irrigation; this reduction is similar to our 24.7% drop in height at 40% FC. (Çakir. 2004) similarly that water stress at various growth stages lowered the vegetative development of corn. (Ji et al., 2012) identified that early drought impacted the leaf area of maize but that much of this was regained after watering, which could help explain why growth was less affected in our moderate treatment compared to the severe water shortage.

The leaf relative water content decreased from 84.6% to 65.4% and the SPAD value fell from 52.3 to 38.7 as water supply reduced. Photosynthesis is one of the processes that is most affected by drought conditions (Chaves et al., 2009), and the decline in leaf hydration, chlorophyll levels, and photosynthetic this trait has been observed in maize genotypes as reported by (Efeoglu et al., 2009). (Song et al., 2018) found that ongoing water shortages drastically restricted the ability of maize leaves to photosynthesize, while (Ye et al., 2020) observed that a lack of water after silking expedited leaf aging in waxy maize. This potentially explains for the substantial 26.0% decrease in SPAD during extreme water scarcity, even though our findings do not indicate the timing of this reduction. (Cai et al., 2020) determined that the reproductive phase is more susceptible to water stress compared to the vegetative phase, suggesting that ongoing shortages during later phases can be particularly harmful. However, the moderate treatment maintained approximately 91% of the control leaf water content and 88% of its SPAD measurement. This supports with the expected partial stomatal control seen in alternate partial root-zone irrigation, where the part of the root system receiving water continues to hydrate while roots in drier soil send out signals that limit stomatal opening (Kang and Zhang, 2004; Davies and Zhang, 1991). (Huang et al., 2022) similarly indicated that a slight deficit during the seedling phase did not considerably impact net photosynthesis, stomatal conductance, or transpiration, whereas shortages in later phases significantly reduced these factors.

Root biomass was greatest at 60% field capacity (86.7 grams per plant, 10.9% higher than the control), and the ratio of root to shoot increased from 0.250 to 0.314, subsequently declining to 61.9 grams per plant at 40% field capacity. Increased root allocation under conditions of moderate water scarcity is well established: (Poorter et al., 2012) conducted a meta-analysis indicating that plants typically increase their root mass fraction when water availability reduced, (Comas et al., 2013) examined root characteristics that enhance productivity during drought, and (Blum. 2005) maintained that sustained water absorption through root development is crucial for maintaining yield stability under stress. Research into varying irrigation methods in maize supports this perspective. (Kang et al., 1998) observed that maize plants with divided roots exhibited heightened water use efficiency when subjected to alternating irrigation, while (Kang et al., 2000) discovered that alternate furrow irrigation could lessen water usage in maize in arid regions without significantly impacting yield. Furthermore, (Li et al., 2007) revealed that the advantages of Alternate Partial Root Irrigation for maize growth, as well as for the efficiencies of water and nitrogen use, were influenced by fertilization practices and soil moisture conditions. This final observation is significant as it suggests that the response of roots is contingent upon the soil moisture level, correlating with the peak at 60% field capacity and the decrease at 40% in our investigation, where intense stress likely restricted the supply of assimilates to both shoots and roots (Farooq et al., 2009; Lawlor and Cornic, 2002). Root length, depth, and distribution were not evaluated; hence the increased ratio should be interpreted as an indication of resource allocation rather than as evidence of deeper root systems.

Grain output decreased by 10.6% at a moisture level of 60% FC and by 35.3% at 40% FC, along with biological yield dropping by 13.5% and 32.0%, thus indicating that a moderate deficit retained 89.4% of the yield seen in control conditions. (Huang et al., 2022) noted that skipping seedling irrigation kept the yield similar to the control while cutting down water usage by 16.9% and boosting water efficiency by 17.3%, whereas water deficits during later growth stages and single irrigation led to yield reductions of as much as 47.3%. Similarly, (Xiao et al., 2011) found that drought conditions during the seedling phase had the least impact on grain yield, whereas drought during the tasseling phase had the most detrimental effects. (Çakir. 2004) and (Hirich et al., 2014) suggesting that water scarcity at later growth stages significantly diminished yield by resulting in fewer grains per ear and smaller grain size. Research from (Zou et al., 2021), (Jin et al., 2020), and (Attia et al., 2021) highlighted that deficits during vegetative stages could enhance or sustain water usage efficiency with minimal yield impact. In contrast, (Farré and Faci, 2009) and (Payero et al., 2009) showed that deficit irrigation in maize conserves water, but the timing of this irrigation critically influences both yield and water use efficiency. The peak harvest index recorded at 60% FC (44.2%) indicates that grain output was better safeguarded than the overall biomass, which aligns with the principles of regulated deficit irrigation (Fereres and Soriano, 2007; Chai et al., 2016). Its decline to 40.7% at 40% FC is in line with the susceptibility of maize's reproductive phase to drought (Herrero and Johnson, 1981), disrupted tassel formation due to water scarcity (Li et al., 2019), and an extended anthesis-silking interval that hinders kernel formation (Bolaños and Edmeades, 1996). Measurements of kernel count, ear characteristics, and the anthesis-silking interval were not conducted in this study, leaving these mechanisms as unproven theories.

Water availability for farming is becoming increasingly limited in semi-arid areas, making deficit irrigation a commonly accepted approach for maintaining food production with reduced water resources (Du et al., 2015). Although, examinations of partial root-zone drying and regulated deficit irrigation highlight that outcomes are influenced by factors such as soil type,

climate conditions, the extent of the deficit, and the timing of irrigation (Chai et al., 2016; Sepaskhah and Ahmadi, 2010). Our findings support with this observation: the moderate level of APRI (60% FC) preserved the majority of the yield and achieved the highest harvest index, whereas the severe level (40% FC) proved to be excessively limiting and should be avoided during the flowering and grain filling phases. In contrast to (Huang et al., 2022), who evaluated evapotranspiration, water use efficiency, and yield response, our data does not include specifics on water usage, genotype variations, or developmental stages, preventing any claims of water-use efficiency advantages and preventing the identification of the stages most impacted by each trait. However, the results indicate that 60% FC appears to be the most advantageous level for further evaluation, employing direct water accounting, monitoring soil moisture, and implementing stage-based scheduling that safeguards tasseling and grain filling, prior to making any recommendations for maize cultivation in Pakistan or similar semi-arid regions.

Conclusion

The overall data indicate that lowering soil-water levels from 100% to 60% and further down to 40% limited the growth of maize. This also affected the plant's leaf moisture, chlorophyll health, shoot biomass, overall biological yield, and the amount of grain produced. The most significant impact came from a severe water shortage, leading to a 35.3% drop in grain production when compared to full irrigation. A moderate water shortage did decrease overall yield but still maintained 89.4% of the yield seen in the control group. This condition resulted in the highest root biomass, the best root-to-shoot ratio, and the top harvest index. These findings suggest that a moderate water shortage within an APRI approach appears to be the best option for future analysis of water productivity. The conclusion is specifically based on the existing data. The document does not assert any specific advantage in water use efficiency because water usage statistics were not provided and it does not include rankings by genotype or growth stage that cannot be verified from the tables presented. APRI should be evaluated as a monitored irrigation method that is aware of different growth stages, rather than being applied as a one-size-fits-all percentage of field capacity. Comprehensive raw data and validation across multiple seasons are essential before recommending practices for maize cultivation in Pakistan or similar semi-arid areas.

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