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Review Article

Relationship of Maize Yield to Climatic and Environmental Factors under Deficit Irrigation: A Quantitative Review

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There is evidence that freshwater resources available for agriculture are decreasing with an unprecedented record. New irrigation strategies are developed and tested on crops that feed the world, such as maize, to improve water productivity. Deficit irrigation is one of these strategies that can improve water productivity without a significant impact on crop production. Here, the authors review the factors that affect the response of maize yield and irrigation water productivity to water stress induced by deficit irrigation using a quantitative approach. Data were collected from peer-reviewed publications worldwide that respond to predefined criteria. The authors defined grain yield variation (GYv) and variation of irrigation water use efficiency (IWUEv) as response variables and used simple and multiple linear regression models for data analysis. Overall, maize response to deficit irrigation is significantly correlated to the water stress level (WD). Mild stress below 20% of optimal irrigation led to 0.5% to 17.45% of yield loss in the vegetative stage (VS) but resulted in 46% yield loss at the reproductive stage (RS). Water stress (20–40%) applied at both vegetative and reproductive stages (VRSs) can reduce yield by 44%. The maximum yield loss was 90% in the RS. The multiple linear regression revealed that 62% of the grain yield variability was explained by both WD and nitrogen rates in the VS, while 54% and 13% of this variability was explained in the RS and VRS, respectively. The authors also found that the WD and the climate explained the best the GYv and the IWUEv under deficit irrigation. These results suggest that regarding the climatic characteristics of site location and the complexity of maize production systems, site-specific levels of deficit irrigation should be recommended to limit yield loss and increase water productivity.

1. Introduction

The world is facing a water crisis affecting every sector and above all, food security [1, 2]. Out of the 3% freshwater available on the Earth, 69% is extracted worldwide for agricultural purposes, mainly for irrigation purposes [3, 4]. A share of 15 to 35% of the irrigation water in low- and middle-income countries is used in an inefficient and unsustainable manner [5]. Much water is lost through excessive water use for crops, soil erosion, high evaporative demand, and runoff. For example, Lake Chad, which was once the largest freshwater lake in Africa, has shrunk by 90% in 40 years, due to irrigation and to some extent, desertification [6, 7]. In the context of climate variability and climate change, a reduction of precipitation, coupled with increased CO_2 emissions, is predicted to affect the water quantity and quality in many areas [8, 9]. In contrast, food demand is projected to increase by 70% by 2050 [5]. These considerations have left the agricultural sector with the double challenge of making 70% more food available to the world's growing population with less or decreasing freshwater resources [10, 11]. One way to overcome this challenge is to shift to irrigation methods and technologies that improve water use efficiency (WUE) [12, 13].

Regulated deficit irrigation (RDI) has been investigated for its potential to increase or maintain crop yield with less water [14]. It is a practice whereby a crop receives an amount of water below the full requirement for its optimal growth to increase WUE. A variant of RDI is the stage-based deficit irrigation, through which a timely application of water to the crop, based on growth stages, and water requirements can substantially increase irrigation efficiency and water productivity [15, 16]. Stage-based deficit irrigation relies on the principle that plant response to water stress varies with the growth stage and that less water applied to plants at water stress tolerant stages may not cause a significant reduction of primary productivity [17]. For this reason, a knowledge of the sensitive growth stages and water requirements at each growth stage is a prerequisite [13]. The sensitivity of a plant's growth stage to water stress can also be affected by many factors, including climatic conditions, crop species, and cultivars, agronomic management practices, among others [17]. Various studies pointed out the reproductive stage as the most sensitive to water stress in major food crops [18–21].

Recent studies have improved the understanding of the physiological and biochemical mechanisms involved in RDI. On a physiological basis, RDI induces a reduction of leaf water potential [22], reduction of photosynthesis rate and respiration [23, 24], and stomatal closure [25], all of which are related and are regulated by chemical signals [17]. Decreased leaf water potential acts as a signalling process, whereby the abscisic acid hormone (ABA) produced in roots and shoots is moved to the leaves and triggers stomatal closure [26]. Although ABA is the central component in the signalling process, antioxidation enzymes [27–30] and nonenzymatic substances [31, 32] produced in leaves and roots also intervene in the defense mechanism of plants under water stress.

One of the obvious benefits that stem from the practice of deficit irrigation is the increase of WUE. This observation remains the same for all growth stages since less water is lost through soil evaporation. If WUE often increases, the case is different for yield. Response of crop yield under RDI varies more with the stage at which the deficit has occurred [13]. When water stress is induced at the seedling stage, there is crop failure in most cases. Similarly, for most crops subjected to RDI at the reproductive stage, yield is always reduced [33]. For example, a short duration of water deficit during the tasseling stage in maize (*Zea mays*) reduced biomass production by 30% and grain yield by up to 40% [34]. The vegetative stage, however, makes an increase in crop yield possible depending on the timing and magnitude of water stress [35]. Nevertheless, there are controversial reports that grain yield may increase or decrease. A slight water deficit of 17.48% in the PR31P41 maize cultivar at the vegetative stage resulted in a 14% reduction in grain yield [36]. Around the same magnitude of water stress in Pioneer brand 3377 cultivars, 9% of yield was reduced [34]. A water deficiency of 80% caused up to a 90% reduction of yield in the McCurdy 84AA maize cultivar [37], suggesting that the more water stress increases, the more yield reduces. On the other side, the authors of [38] found that deficit irrigation applied during the vegetative stage increased maize grain yield by 10 to 20% compared to the stress applied during the whole growth cycle. A study conducted by the authors of [39] showed that 17.2% of deficit irrigation at the vegetative stage resulted in a 5.3% increase in maize grain yield (variety Pioneer 3184) compared to the optimal treatment. More recently, 16.4% and 21.5% of water deficit in the RH-240 maize variety resulted in a 2.9% and 2.3% increase in grain yield, respectively [40]. These results reveal that the variability in grain yield response to water stress is due to the difference in crop cultivars (with comparable water stress and growth stage), and other biotic and abiotic factors nonapparent in the given studies. One question that arises then is what other factors may influence crop response to water stress?

The two main research questions that guided this review are as follows: (i) how does maize crop respond to water deficiency?, what is the relationship between maize yield to climatic and environmental factors in deficit irrigation conditions?, and (iii) what can the authors learn from this analysis to assess water stress levels for optimum grain yield? The objective of this review was to analyze the global relationship of maize grain yield and irrigation water use efficiency to climatic and environmental factors under water deficiency.

2. Methodology

The review process followed four steps: (i) definition of the objective, (ii) literature search and retrieval, (iii) identification of relevant studies and data extraction, and (iv) statistical analysis and interpretation.

2.1. Definition of the Objective of the Review. The dependent variables studied are the grain yield variation or grain yield loss, GY_{V} (1) the variation of irrigation water productivity and $\mathrm{IWUE}_{\mathrm{V}}$ (2) under deficit irrigation conditions compared to no deficit irrigation or optimal irrigation water conditions. A water stress index (WD) has been defined as the ratio of the difference between the optimal irrigation water and the deficit irrigation water over the optimal irrigation water levels. Only treatments where plots were irrigated off the rainfall season were considered for the analysis.

$$\mathrm{GY}_{v} = \frac{\left(Y_{\mathrm{Opt}} - Y_{\mathrm{Str}}\right) * 100}{Y_{\mathrm{Opt}}}, \tag{1}$$

$$\mathrm{IWUE}_{\mathrm{V}} = \frac{\left(\mathrm{IWUE}_{\mathrm{Opt}} - \mathrm{IWUE}_{\mathrm{Str}}\right) * 100}{\mathrm{IWUE}_{\mathrm{Opt}}}, \tag{2}$$

$$\mathrm{WD} = \frac{\left(I_{\mathrm{Opt}} - I_{\mathrm{Str}}\right) * 100}{I_{\mathrm{Opt}}}, \tag{3}$$

where Y is the grain yield (kg/ha) and I the irrigation water amount applied (mm). Opt indicates the optimal treatment where full irrigation water was applied and Str refers to treatments that received deficit irrigation water. IWUE is the irrigation water productivity defined as the grain yield per unit of irrigation water (4)

$$\mathrm{IWUE} = \frac{\text{Grain yield (Kg/ha)}}{\text{Irrigation Water (mm)}}, \quad (4)$$

2.2. Literature Search and Retrieval. The search for published articles was mainly undertaken online from science websites including Google Scholar, AGORA, and Science Direct. For this purpose, the following literature search equation was used: ((Maize OR corn) AND response AND (growth AND stage AND based) AND ((water AND stress) OR (deficit AND water))) OR ((Maize OR corn) AND response AND ((water AND stress) OR (deficit AND water)) AND (vegetative OR reproductive OR (grain AND filling) OR anthesis OR silking)). Reference sections of published papers, working papers, and book chapters were thereafter examined to identify subsequent relevant publications.

2.3. Identification of Relevant Studies and Data Extraction. Peer review papers were selected first based on their title. The title had to indicate that the study was conducted on grain corn (or maize) in water stress or deficit conditions. Abstracts were then examined to check the application of irrigation water at a specific growth stage (seedling, vegetative, reproductive, or maturity). Publications included in this review satisfied the following criteria: (1) they published peer-review journal articles that reported results from experiments, (2) irrigation is applied during at least one specific maize growth stage, and irrigation water amount is provided, (3) when different cultivars are studied, the responses are presented separately for each cultivar, and (4) when maize is subjected to different levels of nitrogen, studies reported the interactive effect of different nitrogen and water stress levels on maize. Studies were considered either under rainfall conditions or under irrigation conditions. Results from rainfed experiments were later excluded given the small number of observations recorded (14), which would not allow for drawing relevant conclusions. Henceforth, studies that were exclusively conducted under irrigation conditions were selected. In these studies, authors applied water stress either by skipping one or more irrigation events or byreducing the irrigation water amount or by using both approaches.

Besides the grain yield, the water deficiency, and the IWUE, the data collected from the selected papers included: the nitrogen rates application, the maize cultivar cycle, and the climate of the study area. In their analysis, the climate of the study areas was represented as in the UNEP climate classification system [41], where each climate was quantitatively defined by an aridity index. The aridity index was defined as the ratio between the mean annual rainfall and the mean annual evapotranspiration [41, 42] as shown in equation. (5).

$$\text{Aridity Index} = \frac{\text{Annual rainfall (mm)}}{\text{Anual evapotranspiration (mm)}}, \quad (5)$$

Data points were extracted both from tables and figures. When the results were presented in the figures, they were digitized using WebPlot Digitizer version 3.8 to easily identify points' values.

2.4. Presentation of the Selected Studies. Nineteen (19) peer-review papers published in English were selected based on the selection criteria mentioned in the above section. In total, 653 data points were collected before averaging across replicates under the same water stress levels and growth stages. After averaging, the number of observations used for statistical analysis was 155 as follows: 41 for the vegetative stage (VS), 59 for the reproductive stage (RS), and 55 for the two stages (VRS), Table S1, Supplementary materials A and C.

Selected studies are distributed across all continents (Figure 1). Most of the studies were carried out in America (Figure 2). In Africa, studies were reported from Niger, Burkina Faso, Soudan, and Ethiopia. Three scales of experiments were recorded from the selected studies: on-farm experiments (noncontrolled environmental conditions), field experiments (semicontrolled environmental conditions), and experiments conducted in a station (under full control of environmental conditions). Approximately, 46%, 26%, and 28% of the observations were recorded from on-farm, field, and station experiments, respectively (Figure 3).

Water stress was applied either at the vegetative growth stage (VS) or at the reproductive stage (RS) or both the vegetative and reproductive stages (VRS). The growth stages were based on the FAO classification system of the maize growth stage (Table S2, Supplementary materials B).

Different yield parameters were measured in the selected studies (Figure 4) with the grain yield being the variable reported by all studies. Other parameters were reported by 5% of the studies selected. The lowest number of observations was recorded for the kernel fresh weight (1.12%), ear fresh weight (1.12%), number of kernels per row (1.12%), tasseling percentage (1.12%), and crop growth rate (1.12%).

2.5. Data Analysis. Descriptive statistics was used to present the distribution of studies and observations across continents and climatic zones. Before the application of inferential statistics, the normality of the grain yield, WD, and IWUE was checked using the Shapiro–Wilk test, and these data were transformed when necessary.

Simple regression analysis was first performed between the response variables GYv and IWUEv, and the water deficit level. Then, multiple regression analysis was carried out by adding the nitrogen rates, the climate, and the cultural growing cycle as other predictor variables. For the multiple regression analysis, a backward regression analysis was performed using the Akaike information criterion (AIC) to identify the predictor variables that significantly influence the GYv and IWUEv. The multiple R-square, the adjusted R-square, and the p value associated with the significance test of the model were used to evaluate the performance of the model. The closer the multiple R^2 and adjusted R^2 were to 1, the better the model. The model was considered significant when the p value was less than 0.05.

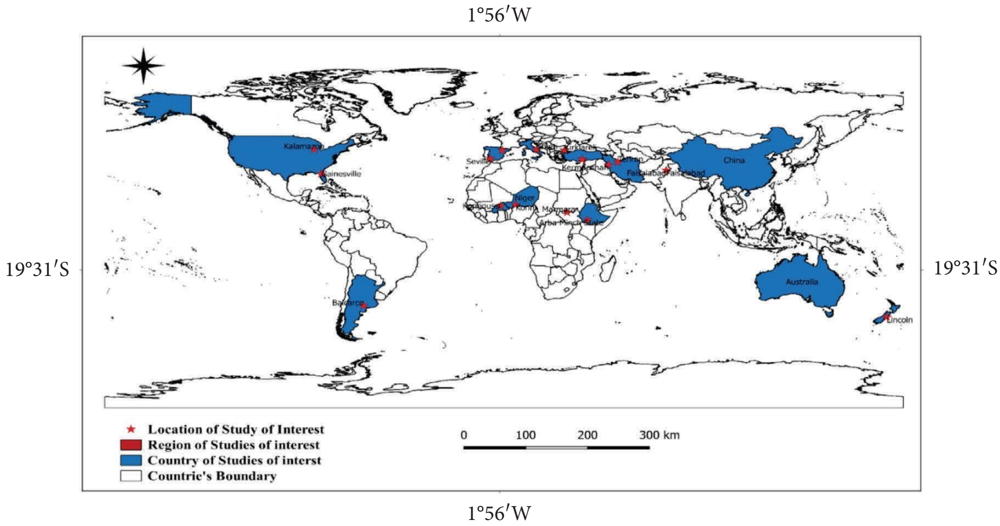


Figure 1: Distribution of locations of studies accounted for in this review.

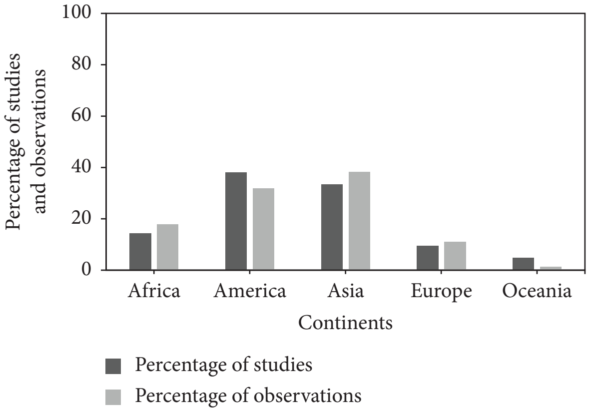


Figure 2: Distribution of studies across continents.

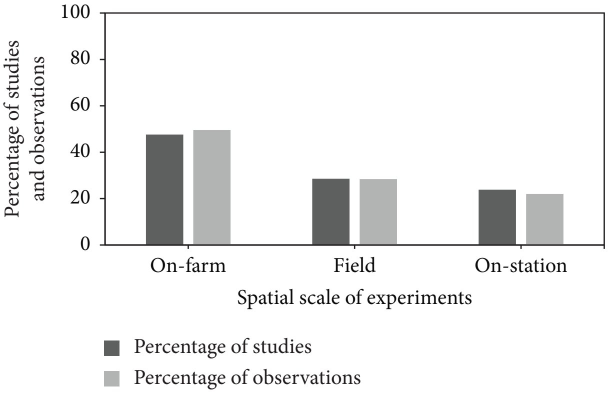


Figure 3: Spatial scale of experiments.

3. Results

3.1. Relationship between Climate and Water Stress Levels Applied. In all growth stages, the more humid the zone, the higher the level of water stress (WD) (Figure 5). In the VS stage, water stress levels did not exceed 30% for the arid and semiarid zones but reached 80% for the dry-sub-humid (DSH) zones. In the RS stage, the highest water stress level zone was 60%, 75%, and 80% for the arid, semiarid, and subhumid climate zones, respectively.

3.2. Maize Grain Yield Loss in Relation to Water Stress Levels and Climatic Zones

3.2.1. Effect of Water Stress Levels (WD) on Grain Yield Loss (GY_V). The GY_V varied with the growth stage when deficit irrigation was applied ($p<0.05$; Table 1). The backward selection indicated that only the water stress level was significantly correlated with the GY_V and $IWUE_V$. Thus, the GY_V was analyzed mainly as a function of the WD. A positive relationship was observed between the GY_V and WD for each growth stage (Figures 6(a)–6(c)). However, the trends varied with the growth stage as indicated by the slope of the linear curves. The slope of the regression is higher for the RS (0.43) and lower for VS (0.15) (Figure 6(a)–6(c)). The WD accounted for 4% of the variance of the GY_V when the stress was applied at the VS (Figure 6(a)). Whereas, 23% and 15% of the GY_V variance was explained by the WD at the RS and VRS, respectively (Figure 6(b) and 6(c)).

In the VS, 86% of the observations were recorded for WD < 20%, among which 51% were between 10 and 20% of WD (Figure 6(a)). Under WD<20% in VS, the GY_V varied from 0.5 to 17.5% of optimal yield. However, for WD>20%, the GY_V reached up to 70% of the optimal yield when WD was around 80%. For RS, 52% and 76% of the observations were below 20% and 40% of WD, respectively (Figure 6(b)). Below 20% of WD at RS, the GY_V was 46% and can be above 90% when WD is around 80%. Whereas, at the VRS, 58% of the observations were recorded above 40% of WD (Figure 6(c)). In the same stage, 0.70 to 30% of GY_V occurred below 20% of WD. A high GY_V of 86% was obtained between 20 and 40% of WD.

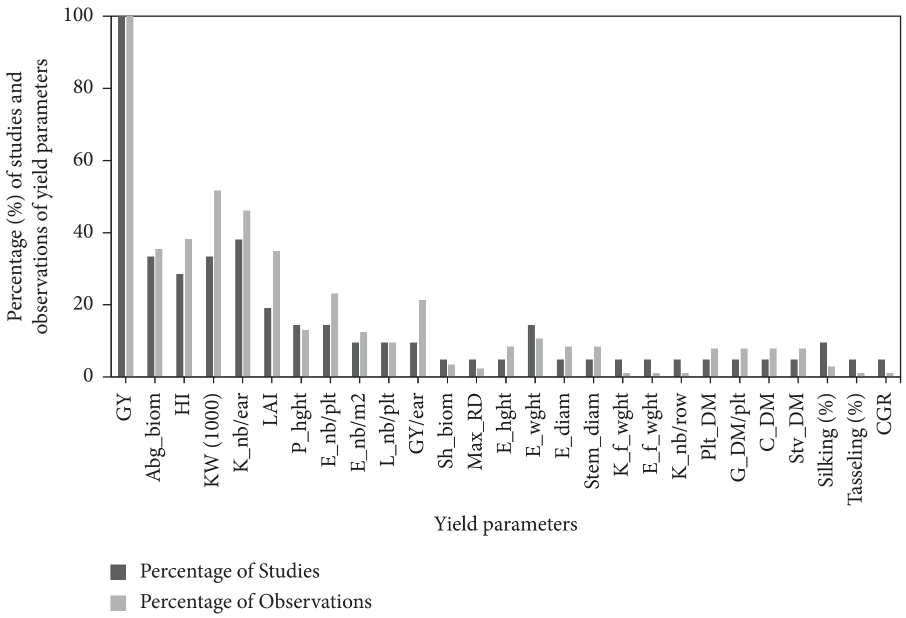


Figure 4: Percentage of studies and observations per yield parameter assessed. GY: grain yield, Abg_biom: above-ground biomass, HI: harvest Index, KW(1000): 1000 kernel weight, K_nb/ear: kernel_number per ear, LAI: leaf Area Index, P_hght: plant height, E_nb/plt: ear number per plant, E_nb/m^2; ear number per m^2, L_nb/plt: leave number per plant, GY/ear: grain weight per ear, Sh_biom: shoot biomass, Max_RD: maximum root depth, E_hght: ear height, E_wght: ear weight, E_diam: ear diameter, Stem_diam: stem diameter, K_f_wght: kernel fresh weight, E_f_wght: ear fresh weight, K_nb/row: kernel number per row, Plt_DM: plant dry mass, G_DM/plt: grain dry mass per plant, C_DM: cob dry mass, Stv_DM: stover dry mass, Silking (%): percentage of silking, Tasseling (%): percentage of tasseling, and CGR: crop growth rate.

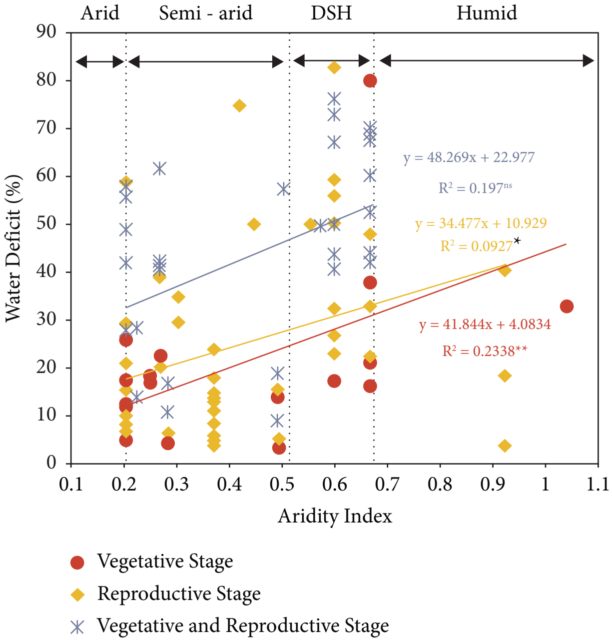


Figure 5: Regression of water deficit levels in relation to the aridity index. DSH: dry-sub-humid climate.

3.2.2. Simultaneous Relationship between the GY$_V$, WD, and AI. In the VS and RS, the higher the water stress and the more humid the climate, the higher the GY$_V$ (Figures 7(a) and 6(b)). However, at the VRS, the GY$_V$ increased as water stress increased but decreased as the climate was humid (Figure 6(c)). In arid zones, the GY$_V$ was higher at the VRS and lower at the VS. In semiarid and subhumid zones, the GY$_V$ was lower at the VRS.

The multiple linear model analysis shows that both the WD and nitrogen rates explained 59%, 22%, and 10% of the variability in GY$_V$ in VS, RS, and VRS, respectively (Table 2).

To improve their understanding, the authors increased the explanatory variables by adding the growing cycle length of the cultivars, and/or the climate of the locations (categorical variable) to the multiple linear regression models. The results (Table 3) showed that the multiple R^2 increased from 62% to 90% in VS and from 13 to 33% in VRS. The adjusted R^2 similarly improved in the same range, from 59 to 89% in VS, 22 to 39% in RS, and 10 to 18% in VRS. In VS, only the climate and WD had a significant effect on GY$_V$ (P value < 0.05). In RS and VRS stages, the model that performed best was the one including the WD and the climate as explanatory variables of GY$_V$.

3.2.3. Effect of Water Stress on IWUE$_V$. IWUE$_V$ varied with the growth stage (Table 1), and increased as the WD increases irrespective of the growth stage. IWUE$_V$ increased with increasing WD in the VS, RS, and VRS, respectively (Figure 8(a)–8(c)), but increase of IWUE$_V$ was more important in the VRS (slope = 1.61, Figure 8(c)). The slope of the trend was lower at the RS (slope = 0.71), compared to the VS (slope = 1.41). A range of 60%, 23%, and 50% of the variability of IWUE$_V$ was explained by water stress at the VS, RS, and VRS, respectively (Table 2).

Table 1: Variation of grain yield and irrigation water use efficiency across maize growth stages.

Growth stages	GY_V	$IWUE_V$
Vegetative	**5.5**^{a}	**8.9**^{ab}
Reproductive	**27.0**^{b}	**4.5**^{a}
Vegetative and reproductive	**21.4**^{ab}	**22.5**^{b}
Significance	<2e-16***	$**$

$^{***}p<0.001$ and $^{**}p<0.01$.

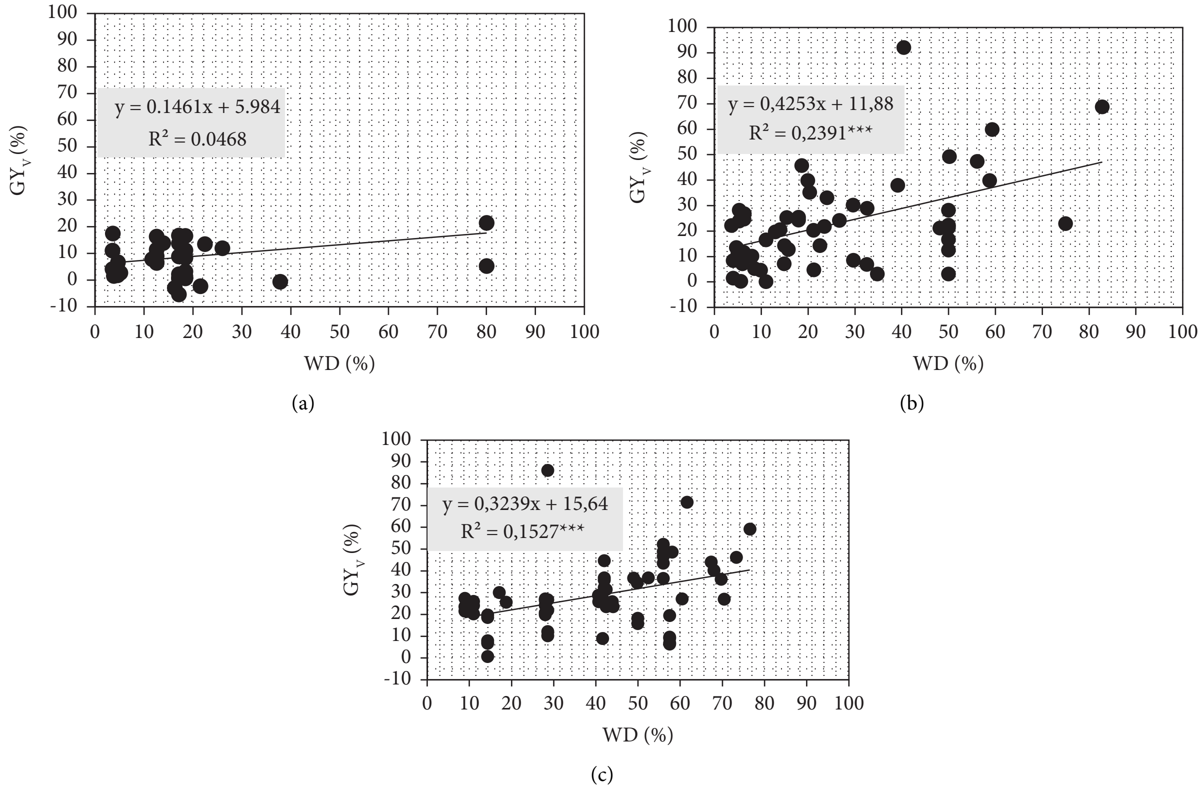


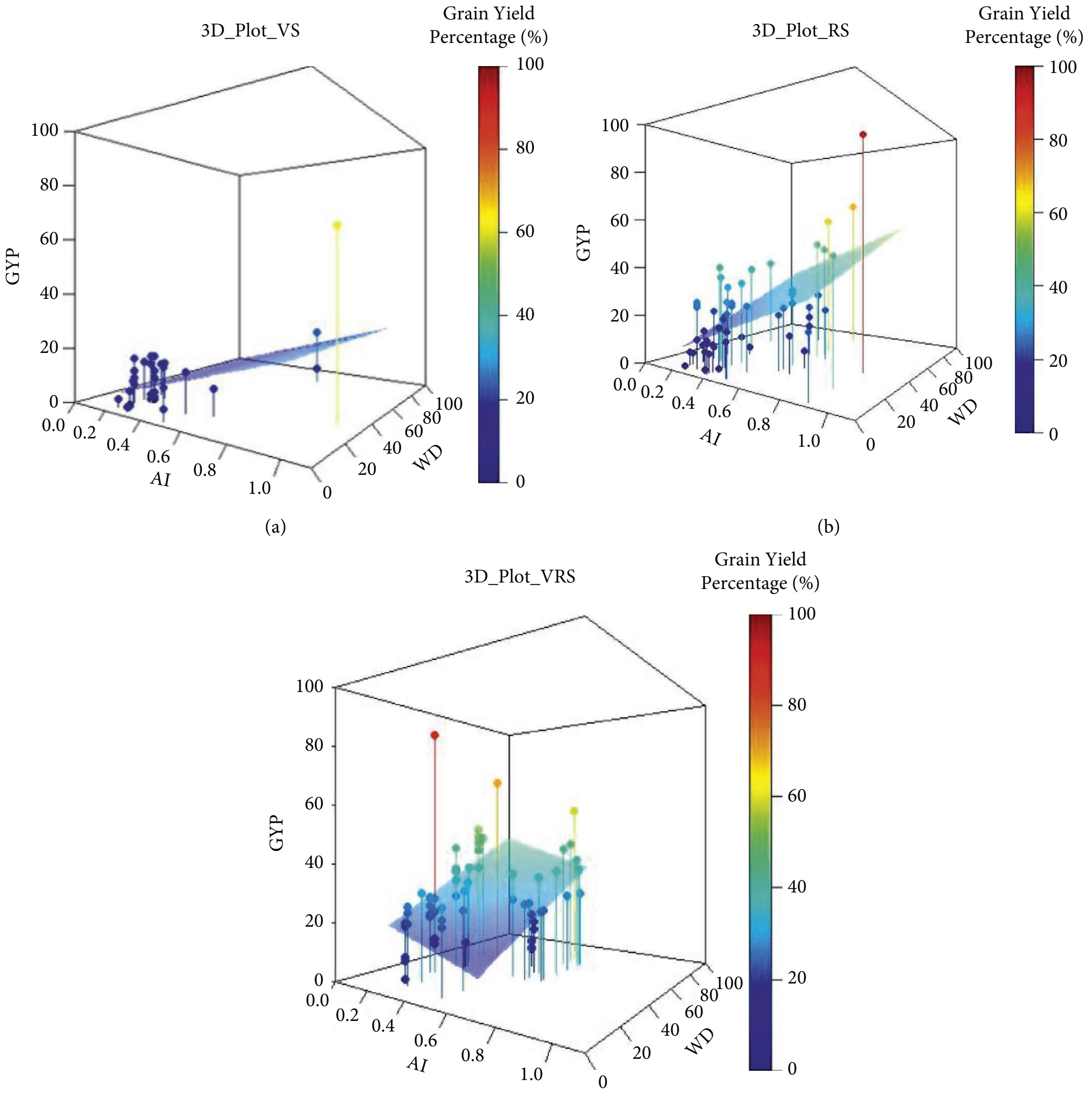
Figure 6: Trend of maize yield loss under deficit irrigation set at (a) vegetative stage, (b) reproductive stage, and (c) at both vegetative and reproductive stages; $^{***}p<0.001$.

4. Discussions

4.1. Climatic Zones of Deficit Irrigation Studies. This review revealed that the selected studies tend to apply higher water stress levels in humid zones than in arid and semiarid zones. The application of lower water deficit levels in arid zones may be a precaution taken to avoid total crop failure under the combination of high deficit level and high evaporative demand. In addition, these observations confirm that much concern is given to deficit irrigation in the arid and semiarid zones to optimize the use of limited water resources for crop production.

4.2. Maize Response to Deficit Irrigation Varies with the Growth Stage. Water deficit at the vegetative stage results in lower yield loss compared to other growth stages (Figures 6 and 7). This explains why the best deficit irrigation strategies target the vegetative stage in the existing literature. In addition, under the comparative water deficit level, yield loss is greater in the reproductive stage than in the vegetative stage. These results concord with previous studies which identified the reproductive stage, namely, anthesis, and the phase immediately following anthesis, as the most sensitive stage to water deficit [43, 44]. The postanthesis photosynthesis greatly determines the most carbohydrates in maize grains, and any stress during that stage would induce considerable yield loss. Moreover, as a C4 plant, maize suffers more from water stress because of the reduced energy captured from sunlight to synthesize carbohydrates during the photosynthesis process. Stomata closure induced by water stress limits the absorption of carbon dioxide, light, and water for the synthesis of carbohydrates.

Under a comparative range of water deficit, yield loss was expected to be higher at both vegetative and reproductive stages than that obtained in vegetative or reproductive stages. Surprisingly, the results of this review shows that the yield loss is even lower when water deficit is applied at both vegetative and reproductive stage compared to yield loss at the reproductive stage. These contrasting results may be



(a)

(b)

(c)

Figure 7: 3D plot of grain yield variation (grain yield percentage) in relation to water deficit level (WD) and climatic zones represented by the aridity index (AI) at (a) vegetative stage, (b) reproductive stage, and (c) vegetative and reproductive stage.

explained by a possible accommodation of the crop to the stress from the early vegetative growth stage, which may have resulted in yield compensation under additional stress at the reproductive stage. As indicated by the authors of [45], when the crop is not subject to water deficit at the vegetative stage before a water deficit occurs at the reproductive stage, yield loss is higher. In other words, applying water deficit to a crop at its early vegetative stage limits yield loss, when water deficit occurs later at the crop reproductive stage.

Since yield loss can substantially be avoided at the crop's vegetative stage, it is essential to identify a specific period at which the crop would be subject to stress with no significant yield loss. Indeed, a slight to moderate degree of water stress at the early vegetative growth stage can maintain or even increase yield [46]. The observations made from this analysis confirm that statement as the lowest yield loss was recorded in treatments that underwent water stress in the early vegetative stage [39]. Furthermore, exceptional observations were recorded where some yield was gained under water deficit in the vegetative stage. These cases represented 10% of the observations at the vegetative stage and the gain of grain yield ranged from 0.5 to 5% of optimal treatments' yield [39, 40].

4.3. Factors Explaining Variability in Maize Grain Yield and $IWUE_V$ under Deficit Irrigation. The GY_V and $IWUE_V$ increase as the water deficit increases. An increase of $IWUE_V$ irrespective of growth stage indicates that globally, high grain yield can be achieved per unit of irrigation water in

Table 2: Multiple linear regression model of $\mathrm{GY_V}$ and $\mathrm{IWUE_V}$ for different growth stages.

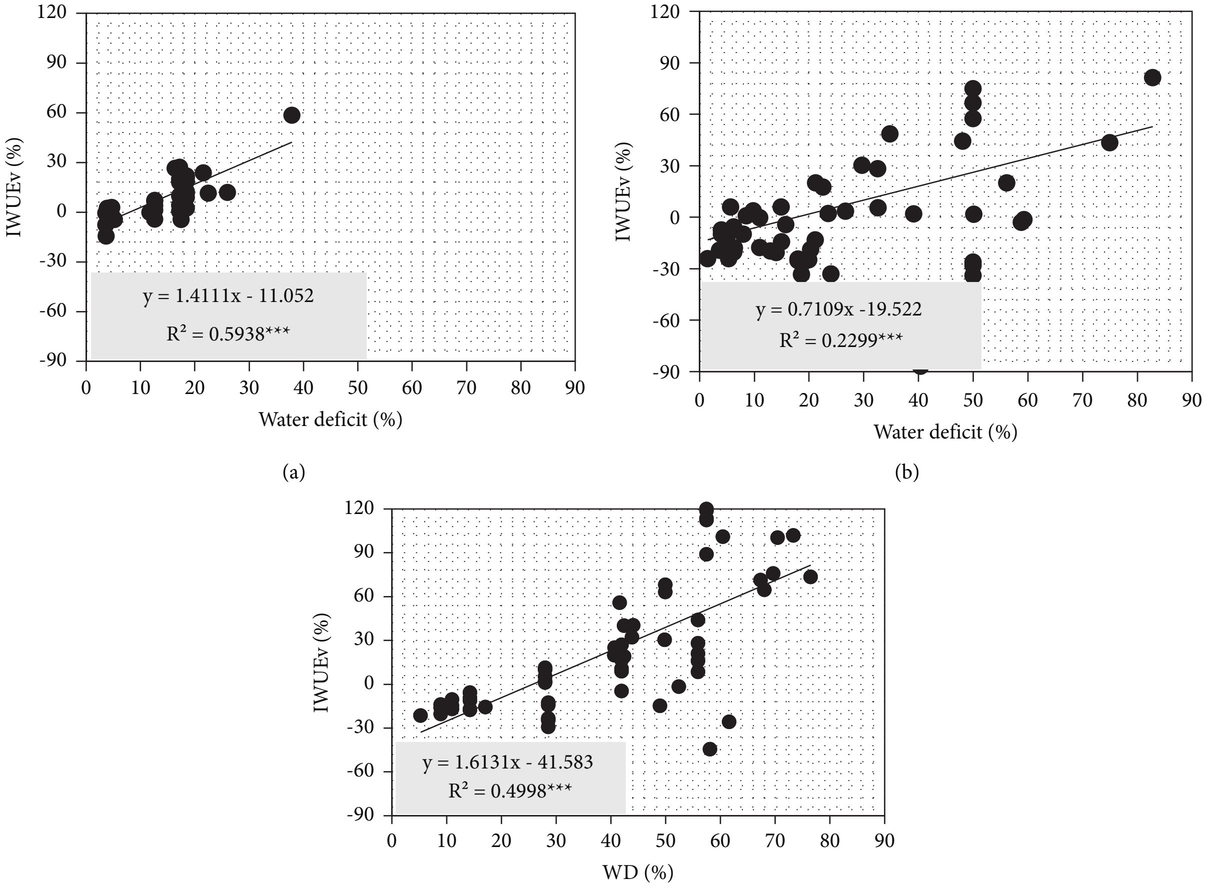
Sources of variation	GY_V Estimates	Standard error	$IWUE_V$ Estimates	Std error
Vegetative stage				
Intercept	−4.16	3.60	−11.98	4.12^{**}
Water deficit percentage	0.86	0.12^{***}	1.42	0.21^{***}
Nitrogen rate	0.0005	0.018	0.006	0.015
Adjusted R^2	0.59		0.57	
Multiple R^2	0.62		0.60	
P value	<0.001		<0.001	
Reproductive stage				
Intercept	6.77	5.78	−14.50	9.80
Water deficit percentage	0.45	0.11^{***}	0.68	0.18^{***}
Nitrogen rates	0.02	0.02	−0.02	0.03
Adjusted R^2	0.22		0.21	
Multiple R^2	0.54		0.24	
P value	<0.001		<0.001	
Vegetative and reproductive stage				
Intercept	12.67	5.89^{*}	−18.81	16.12
Water deficit percentage	0.32	0.11^{**}	0.66	0.29^{*}
Nitrogen rates	0.02	0.02	0.11	0.05^{*}
Adjusted R^2	0.10	0.09		
Multiple R^2	0.13		0.12	
P value	0.016		0.03	

$^{***}p<0.001$, $^{**}p<0.01$, and $^{*}p<0.05$.

Table 3: Results of the best regression model of $\mathrm{GY_V}$ and $\mathrm{IWUE_V}$ for different growth stages.

Sources of variation	GY_V Estimates	Standard error	$IWUE_V$ Estimates	Standard error
Vegetative stage				
Intercept	9.61	2.00^{***}	−14.63	3.76^{***}
Water deficit percentage			1.21	0.20^{***}
Dry-subhumid	−8.82	3.61^{*}	16.14	5.01^{**}
Humid	59.5	4.01^{***}		
Semiarid	−2.83	2.4	7.39	3.07^{*}
Adjusted R^2	0.89		0.68	
Multiple R^2	0.90		0.71	
P value	<0.001		<0.001	
Reproductive stage				
Water deficit percentage	0.42	0.11^{***}	0.32	0.17
Dry-subhumid	6.08	6.52	23.98	10.45^{*}
Humid	39.33	9.14^{***}	−45.54	14.66^{**}
Semiarid	5.56	5.2	−9.66	8.33
Adjusted R^2	0.39		0.46	
Multiple R^2	0.44		0.50	
P value	<0.001		<0.001	
Vegetative and reproductive stage				
Intercept	18.76	6.84^{**}	91.9	64.83
Water deficit percentage	0.29	0.13^{*}	0.56	0.42
Dry-subhumid	0.41	5.36	16.44	23.27
Humid	−17.28	6.75^{*}	51.05	17.98^{**}
Semiarid	−2.55	5.55	14.35	14.33
Nitrogen level			0.08	0.05
Cultivar cycle			−1.06	0.51^{*}
Adjusted R^2	0.18		0.28	
Multiple R^2	0.23		0.36	
P value	0.004		<0.001	

$^{***}p<0.001$, $^{**}p<0.01$, and $^{*}p<0.05$.



(a)

(b)

(c)

Figure 8: Trend of $IWUE_V$ under deficit irrigation set at (a) vegetative stage, (b) reproductive stage, and (c) at vegetative and reproductive stages; $^{***}p<0.001$.

water deficit treatment than optimal irrigation treatment. Even though water stress is significantly correlated to grain yield and explains part of the variation of GY_V and $IWUE_V$ proportions in the VS and RS, one should not overlook the percentage of the variance that remains unexplained by water stress alone. This implies that other factors than water stress explain better the variability observed, particularly at the reproductive stage. Deep insights into the results suggest that maize grain variability is observed at different levels. On the one hand, at the level of growth stage, there is variability among treatments of the same water stress level and from the same climatic regions. To illustrate this, in the humid temperate regions, 50% of the water deficit in the RS induced 49% of grain yield loss on one side [34] and caused 3.20% of yield loss on another side [47]. Similarly, in the hot semiarid climate, 28% of water deficit in the VRS induced 21% of maize grain yield loss in P3Kollo cultivars [48], while the same level of water deficit caused 86% of yield loss in Pioneer 31-R-88 cultivar [49]. On the other hand, there is variability among treatments under equivalent water stress levels and in different climatic regions. A water deficit of 15% induced a 14% of yield loss in the Hybrid Keytar KX-8615Bt cultivar in a cold dry temperate climate and a 25% of yield loss in T. C647, respectively in a hot dry temperate climate. This example suggests that the difference in climatic conditions coupled with the difference in cultivar potential explains the variability of yield loss. Furthermore, the general variability of grain yield under WD reflects a parallel discrepancy of optimal yield among optimal treatments across studies. For instance, the grain yield under optimal irrigation (OI) was 1792 $kg{\cdot}ha^{-1}$ in Niger [47], whereas the grain yield under OI was 20520 $kg{\cdot}ha^{-1}$ in Turkey [36]. Another way this discrepancy was exhibited is that some treatments under water deficit in the VS or RS in one region resulted in higher yield compared to treatments under OI in other regions. This is highlighted by comparing a grain yield of 18060 $kg{\cdot}ha^{-1}$ under 745 mm of irrigation water and 100 $kg{\cdot}ha^{-1}{\cdot}N$ [36], and a grain yield of 8205 $kg{\cdot}ha^{-1}$ under the same water and nitrogen amount [31]. Therefore, despite the strong correlation between yield loss and water deficit at all growth stages, factors such as climatic conditions and the inherent potential of the cultivar could be other sources of variance.

4.4. Implications and Opportunities. It is widely recognized that the agricultural sector is the largest consumer of water resources in the world [49, 50]. With stage-based deficit irrigation (DI), there is a potential opportunity to save the amount of water used in irrigation [46, 52], and hence, increase irrigation water use efficiency [17]. More probably, DI offers an opportunity to increase grain yield. While the increase in water use efficiency is observed generally, the increase of grain yield under DI is still elusive. Previous reviews on DI have either been explanative, focusing on the mechanisms (physiological and biochemical) by which plants respond to DI [17], or comparing types of crop response under different approaches of DI during the plant growing cycle [53, 54]. The present analysis, which focuses on maize response to DI, agrees with previous reviews on the fact that yield penalties caused by DI based on growth stage are compensated with some irrigation water productivity gains. However, the extent to which the deficit irrigation should be limited at each growth stage to reduce yield loss and increase IWUE remains explorative.

Although crop yields are the ultimate target for farmers in any irrigation strategy, this goal can be compromised by saving water in arid environments where water has a higher economic value for crop production [55]. Consequently, there is a need to be aware of the factors that could potentially hinder the effectiveness of water-saving strategies. The results of their analysis showed that maize response to DI varies not only with the growth stage but also with a diversity of factors inherent to production systems.

Among these factors, the climate has a very significant effect on yield under DI. Recent studies proved that temperature and solar radiation are the main climatic parameters explaining maize yield under water deficit [56, 57]. However, since high temperatures are often recorded in drought periods, it is unclear how high-temperature impacts yield under water stress at specific growth stages. Despite the undeniable roles of temperature and solar radiation in the process of crop growth, their significant effects on yield at each growth stage under deficit irrigation need to be investigated.

This review contributes to the recognition that the yield loss induced by water stress is higher in the reproductive stage than in the vegetative stage [13, 45, 46]. Yield gain can be observed under water deficit at the vegetative stage although this can not be generalized. From our review, only a few case studies have been recorded which represent 10% of the total VS observations. However, this provides an opportunity to investigate the appropriate level of water stress to be applied in the early vegetative stages for irrigation decision making. Mainly, for maize crops, the focus should rather be on the variability of water productivity under deficit irrigation. Since yield loss is inevitable irrespective of the growth stage, there is a need to optimize yield loss in conjunction with water productivity gain under a range of factors that are site-specific [58].

5. Conclusion

In this quantitative review on maize response to irrigation water stress, results revealed that the maize crop is more sensitive to DI at its reproductive stage (RS) than any other stage, with the highest yield loss compared to the vegetative stage. Under low stress (20%), maize yield loss varied from 0.5% to 17.45% at the VS, from 1.5 to 46%. at the RS, and from 0.70 to 30% at the VRS. Lower yield loss is achieved at all stages for lower water stress. More important, yield loss was reduced when the stress occurred in the early vegetative stage or the late reproductive stage (dough R4, dent R5, and at physiological maturity R6), provided that the crop suffered no stress at the establishment and beginning of the reproductive stage. Maize yield variability under water stress was not explained only by water stress, but also by external factors such as the climate, the cultivar cycle, and nitrogen rates. However, the significant effect of these factors combined varies from one stage to the other. Water stress and climate greatly explained yield variability in the vegetative and reproductive stages. When stress occurs at both vegetative and reproductive stages, all factors were explanative. With regard to IWUE, much irrigation water can be saved in maize stressed both at vegetative and reproductive stages. However, further analyses are needed to investigate the influence of other factors such as the deficit irrigation frequency, and soil properties at each growth stage.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Supplementary Materials A: Characteristics of the studies included in the review. Supplementary Materials B: Maize growth stage based on FAO classification. Supplementary Material C: List of selected studies. (*Supplementary Materials*)

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